RPC for Positron Emittion Tomography

Discussion

- What is PET
- Why PET/MRI
- RPC as PET detectors
- Human PET
- Small animals PET
- RPCPET project

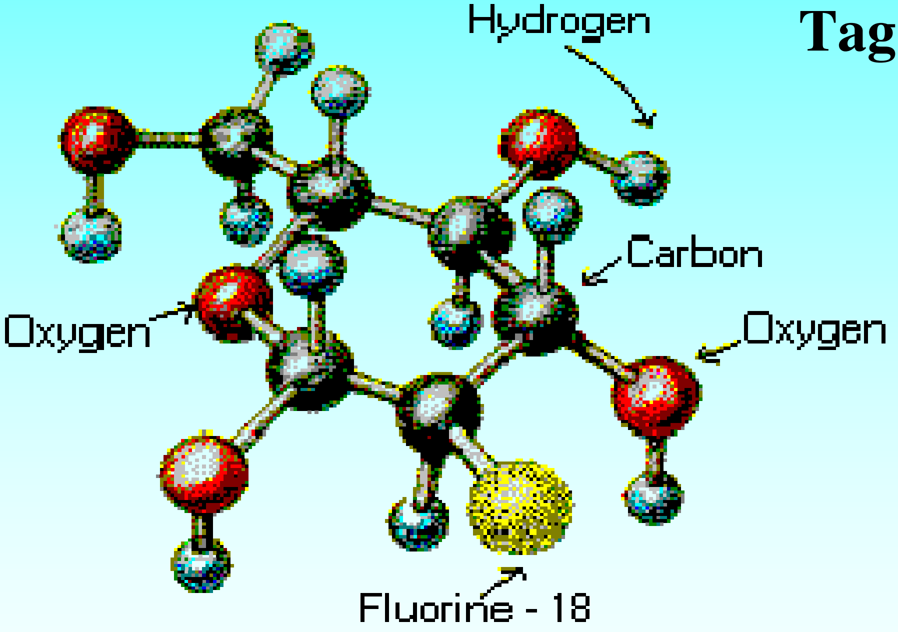
What is PET

What is and How PET works

Positron Emission Tomography (PET) is a radiotracer imaging technique, in which tracer compounds labelled with positron emitting radionuclides are injected into the subject of the study. These tracers compounds can then be used to **track biomedical** and **physiological processes**.

What is PET

2-fluoro-
2-deoxy-D-glucose
"FDG"

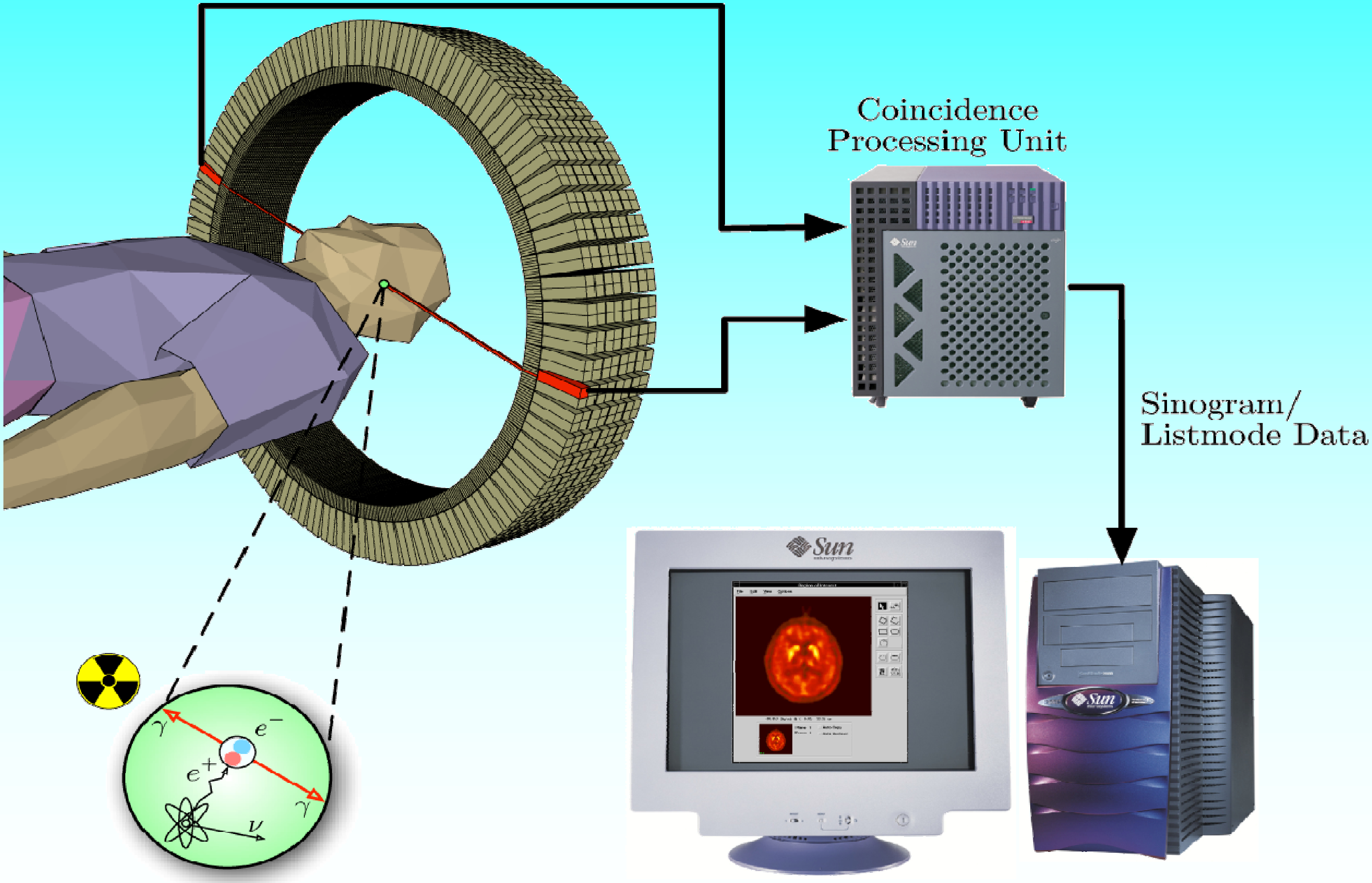


Often used PET radio-isotopes

Tagged atom	half decay time
^{11}C	20.3 min
^{15}O	2.03 min
^{18}F	109.8 min
^{75}B	98.0 min
^{13}N	~10 min

Radionuclides are coupled with molecules used by the organism (glucose, water etc). They are injected into the body and their distribution is followed by the PET.

What is PET

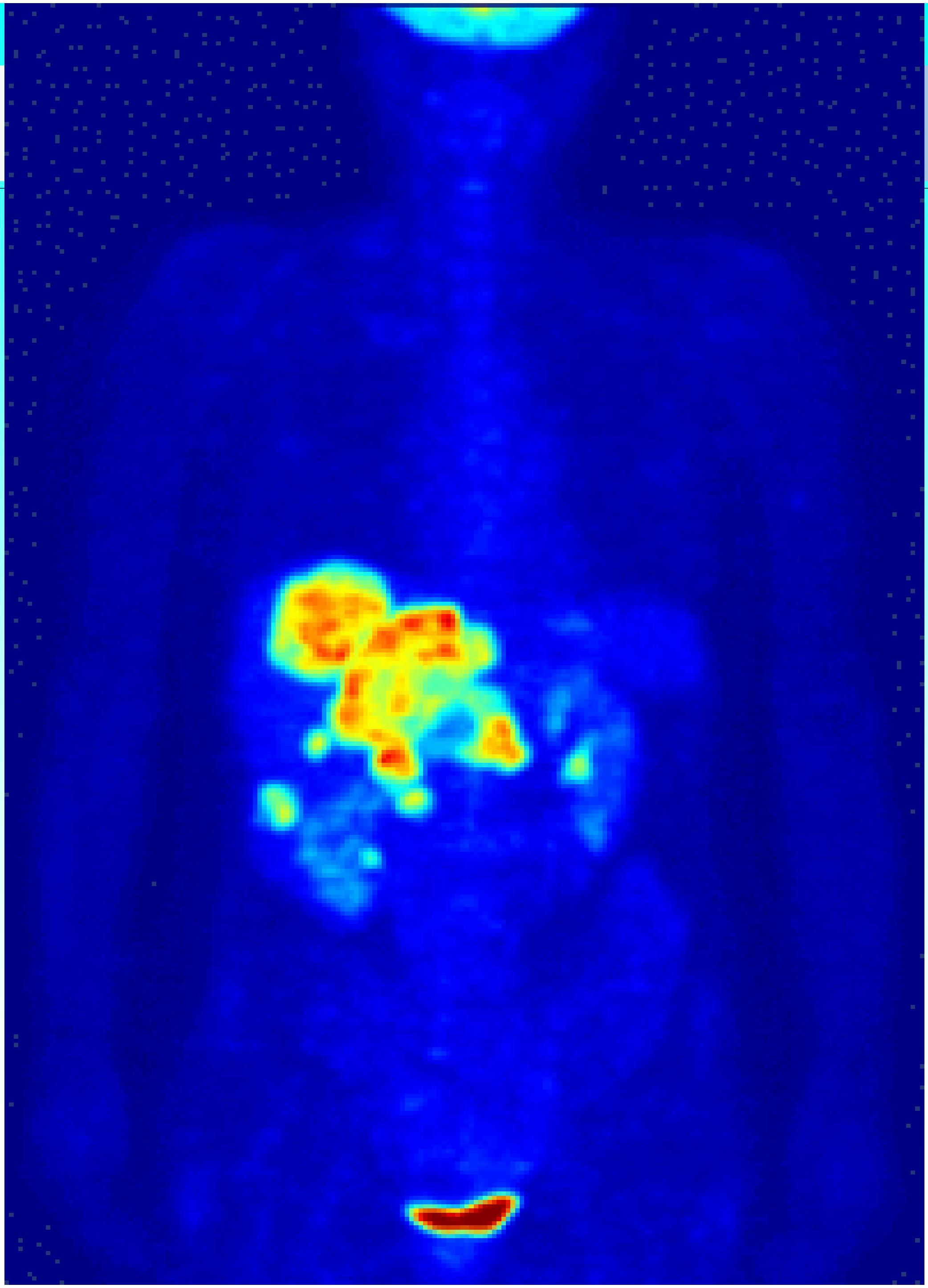


Coincidence Processing Unit

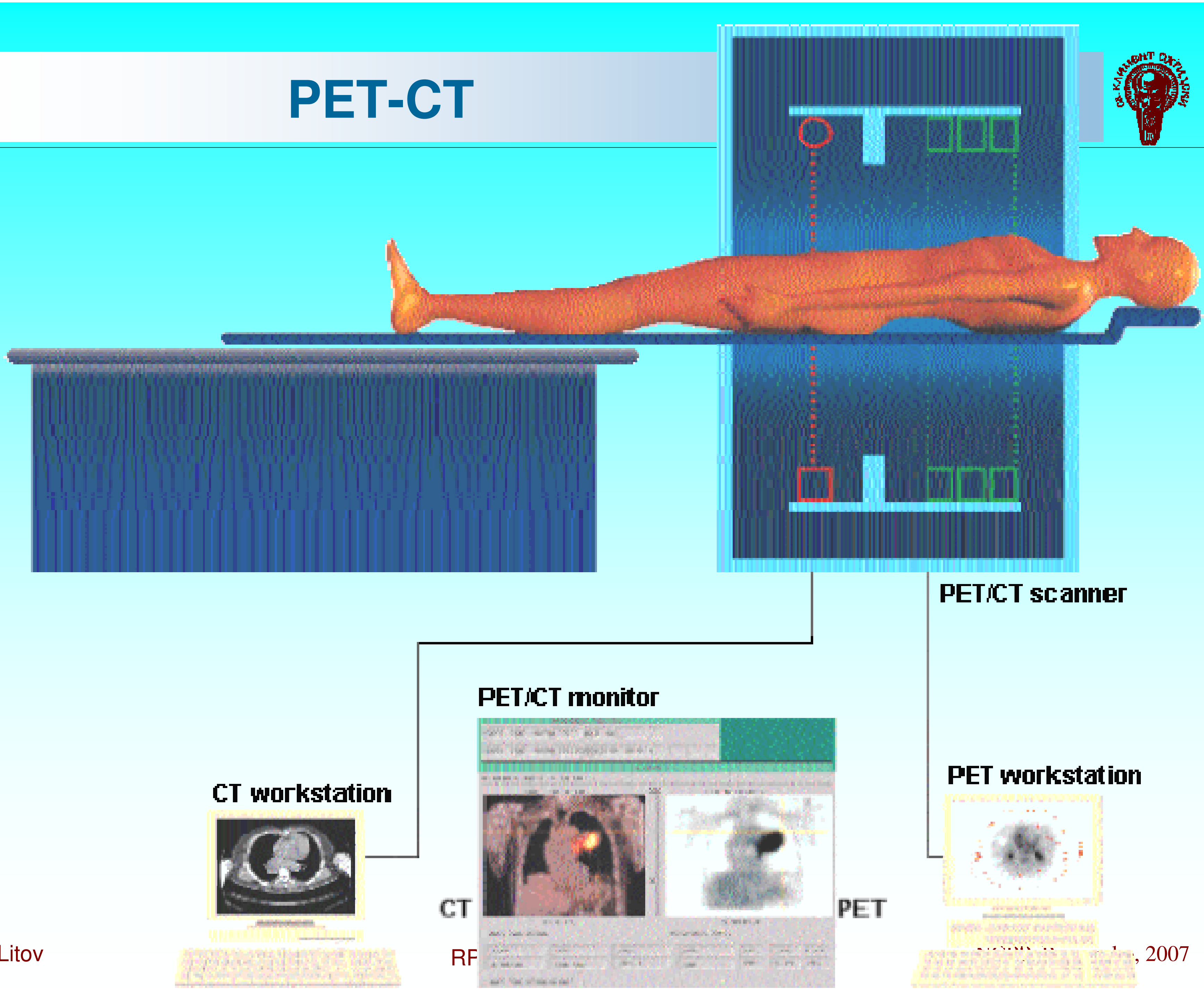
Sinogram/ Listmode Data

Annihilation

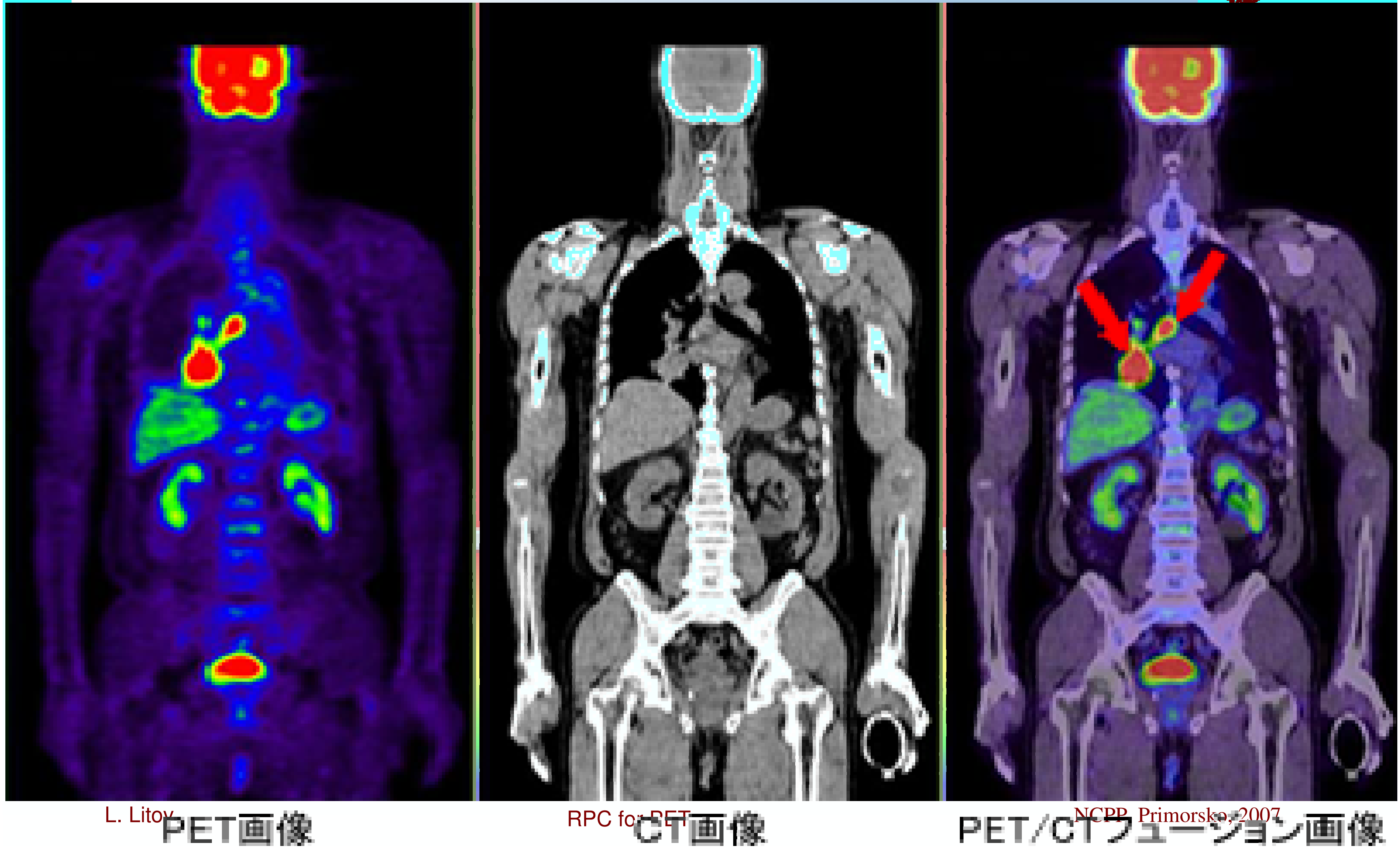
Image Reconstruction



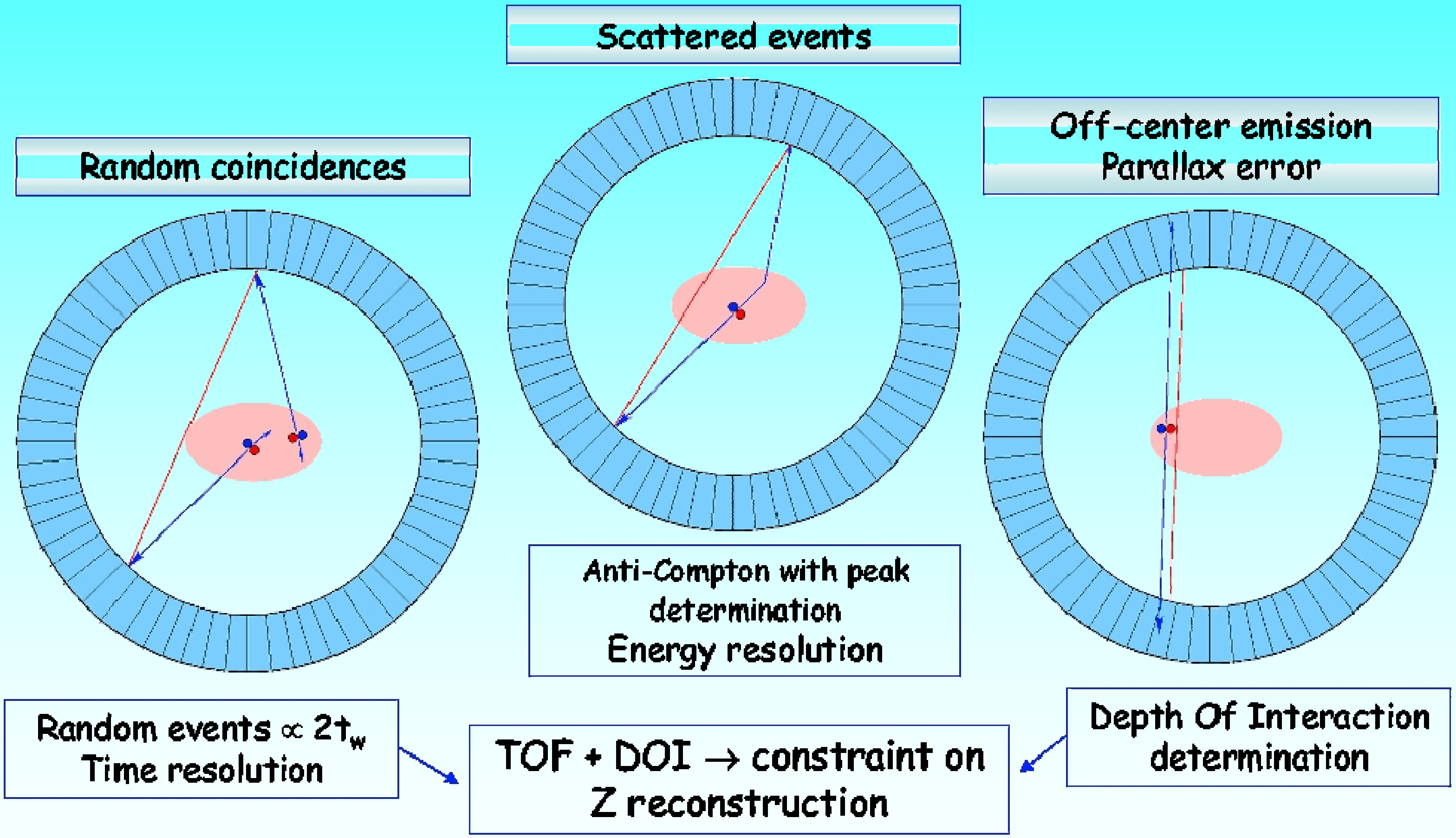
PET-CT


PET/CT scanner
PET/CT monitor
CT workstation
PET workstation
CT
PET

PET-CT



Problems



Scattered events

Random coincidences

Off-center emission
Parallax error

Anti-Compton with peak determination
Energy resolution

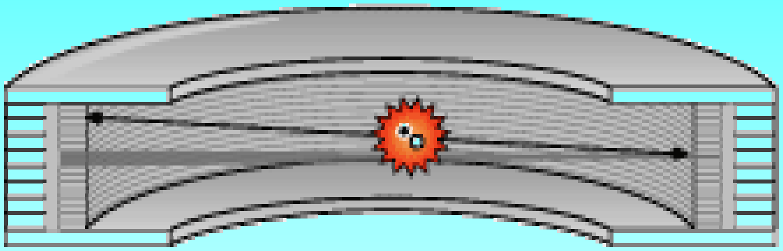
Random events ∝ $2t_w$
Time resolution

TOF + DOI → constraint on Z reconstruction

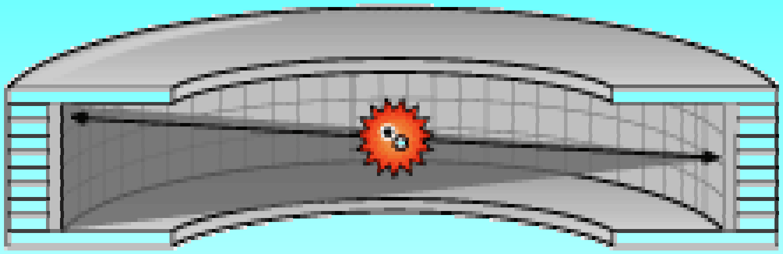
Depth Of Interaction determination

2D and 3D reconstruction

2D and 3D Acquisition in PET



As shown above, 2D acquisition geometry uses shielding (septa) in front of the detectors to restrict the acceptance angle for coincidence events. This limits the system sensitivity and results in longer scan times.



In the 3D acquisition geometry, no shielding is used and the acceptance angle is maximized. The overall system sensitivity is increased, allowing flexibility in patient dosage and scanning time.

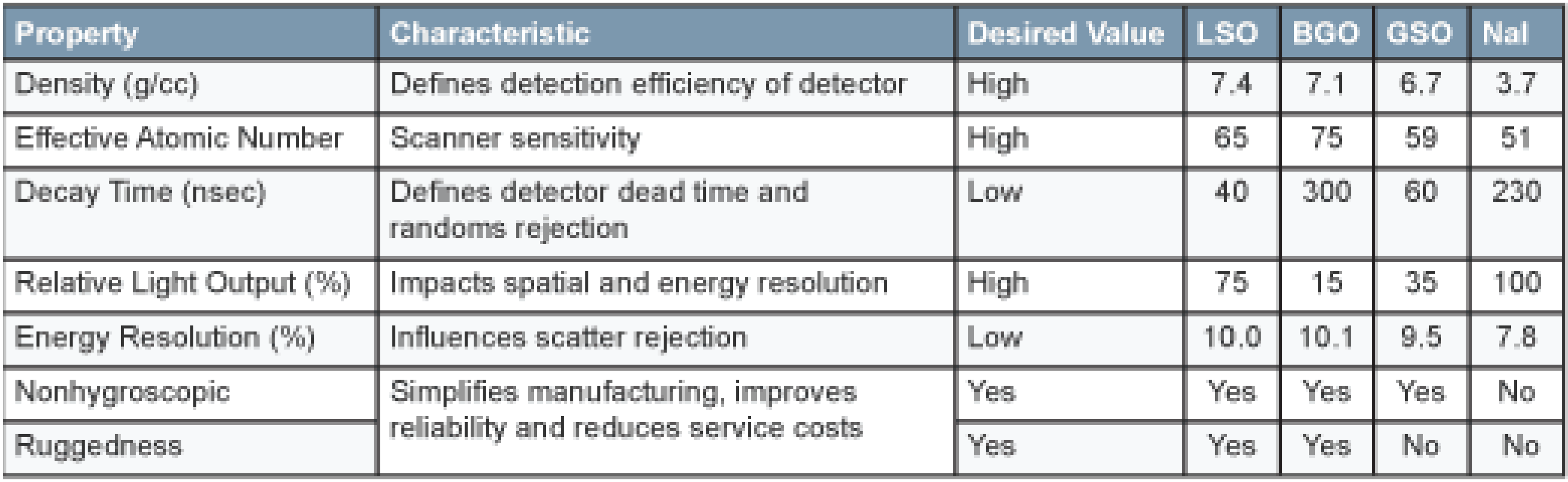
In order to do 3d reconstruction, it is extremely important to introduce corrections for absorption and scattering of the γ inside the body Requires precise MC, individual for the particular patient.

Scintillators

Gamma interactions – photo-effect and Compton scattering

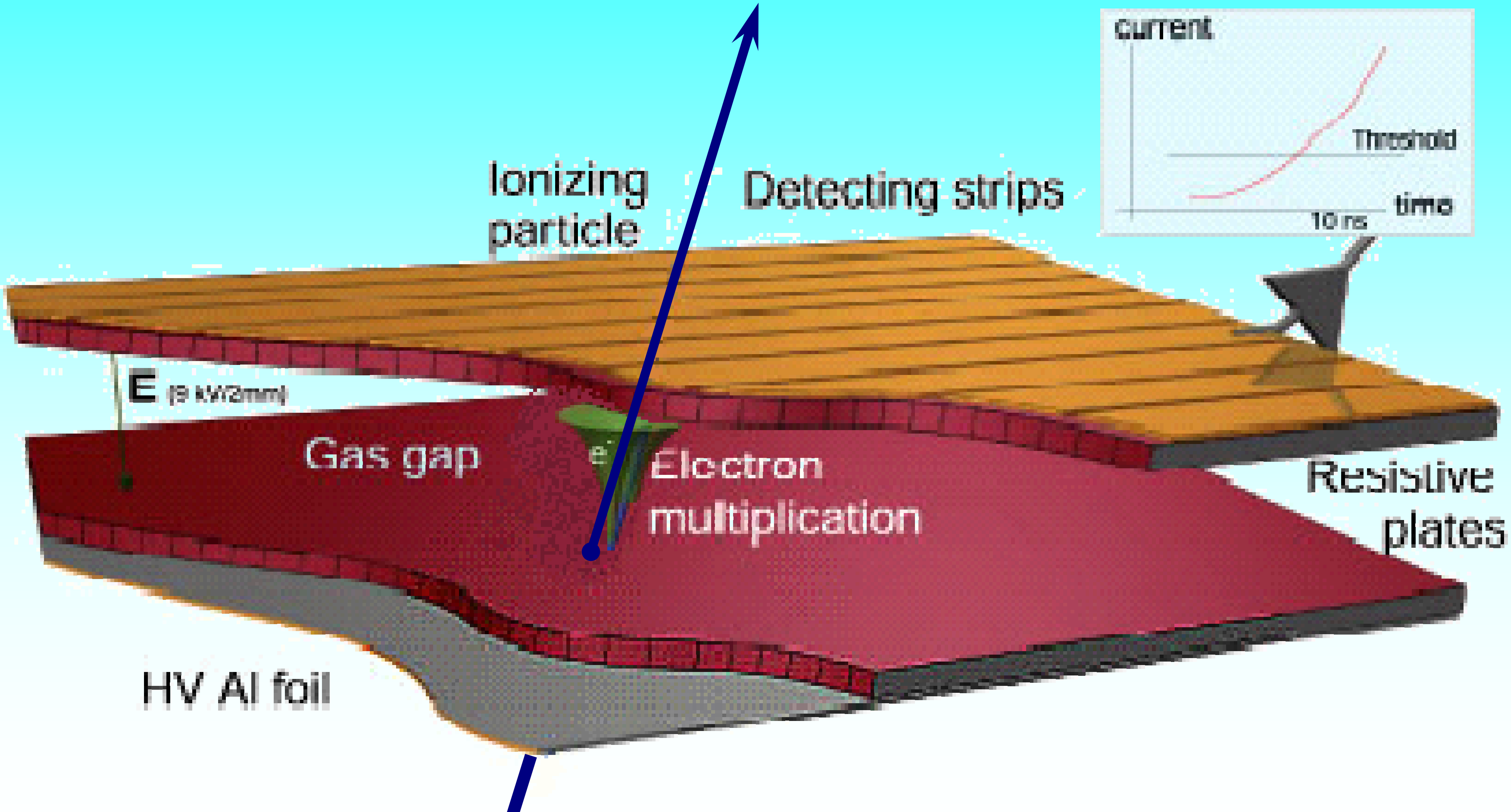
Require materials with high Z and density

Commercially available PET use scintillating crystals to detect gammas



Property	Characteristic	Desired Value	LSO	BGO	GSO	NaI
Density (g/cc)	Defines detection efficiency of detector	High	7.4	7.1	6.7	3.7
Effective Atomic Number	Scanner sensitivity	High	65	75	59	51
Decay Time (nsec)	Defines detector dead time and randoms rejection	Low	40	300	60	230
Relative Light Output (%)	Impacts spatial and energy resolution	High	75	15	35	100
Energy Resolution (%)	Influences scatter rejection	Low	10.0	10.1	9.5	7.8
Nonhygroscopic	Simplifies manufacturing, improves reliability and reduces service costs	Yes	Yes	Yes	Yes	No
Ruggedness		Yes	Yes	Yes	No	No

RPC


current
Threshold
time
10 ns
Ionizing particle
Detecting strips
E (9 kV/2mm)
Gas gap
e
Electron multiplication
Resistive plates
HV Al foil

RPC for PET

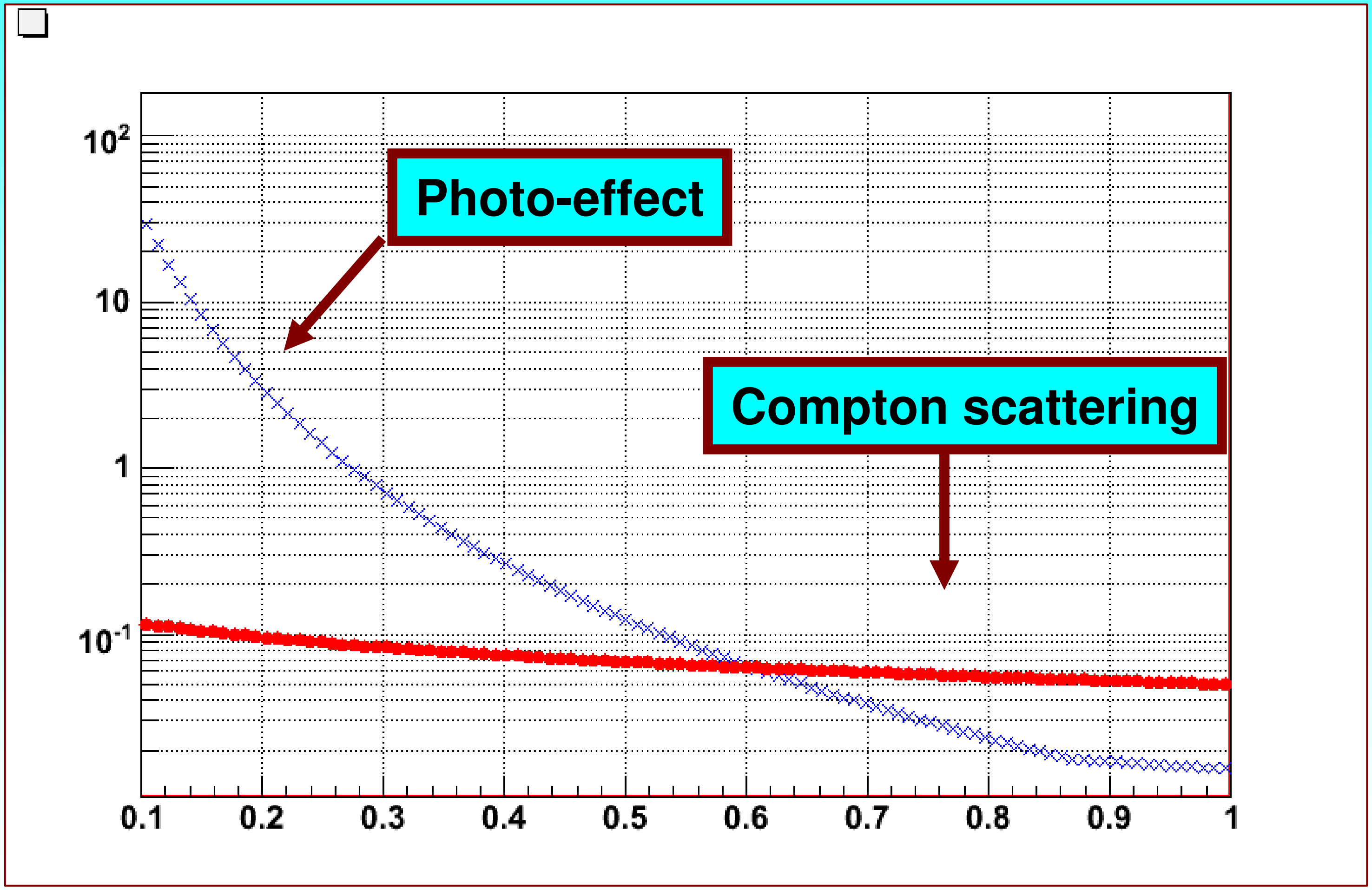
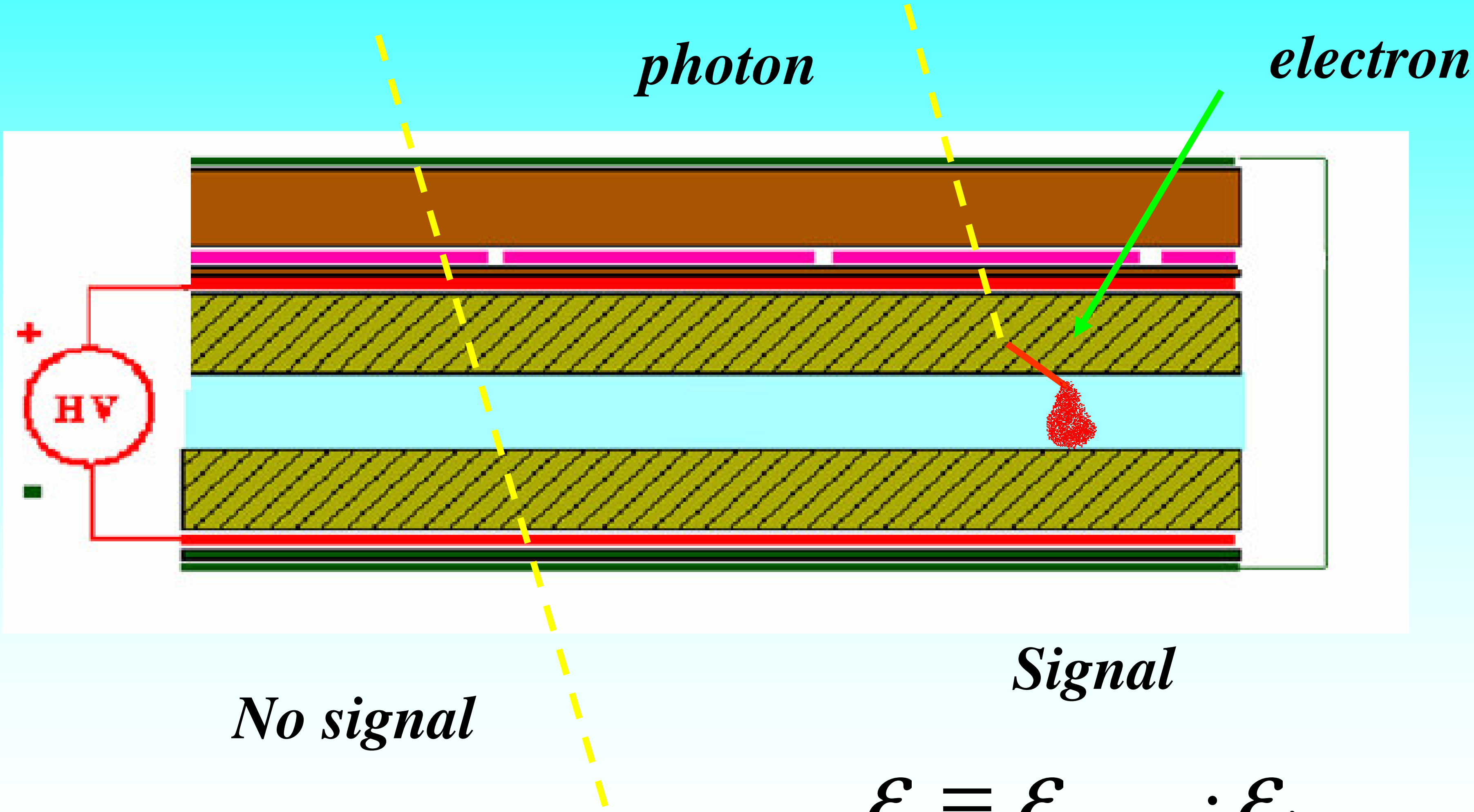


Photo-effect

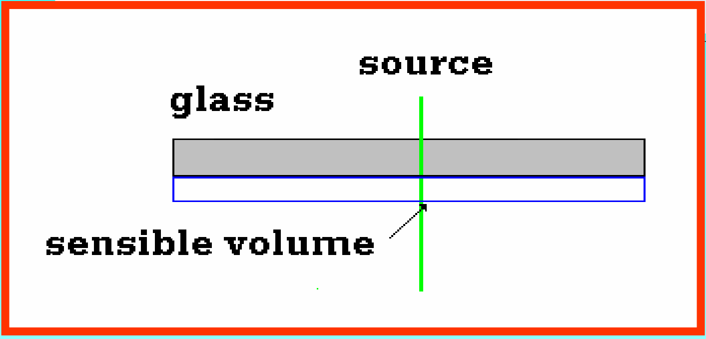
Compton scattering

Neutral radiation (photons)



$$\varepsilon = \varepsilon_{\text{conv}} \cdot \varepsilon_{\text{intr}}$$

Electrode thickness

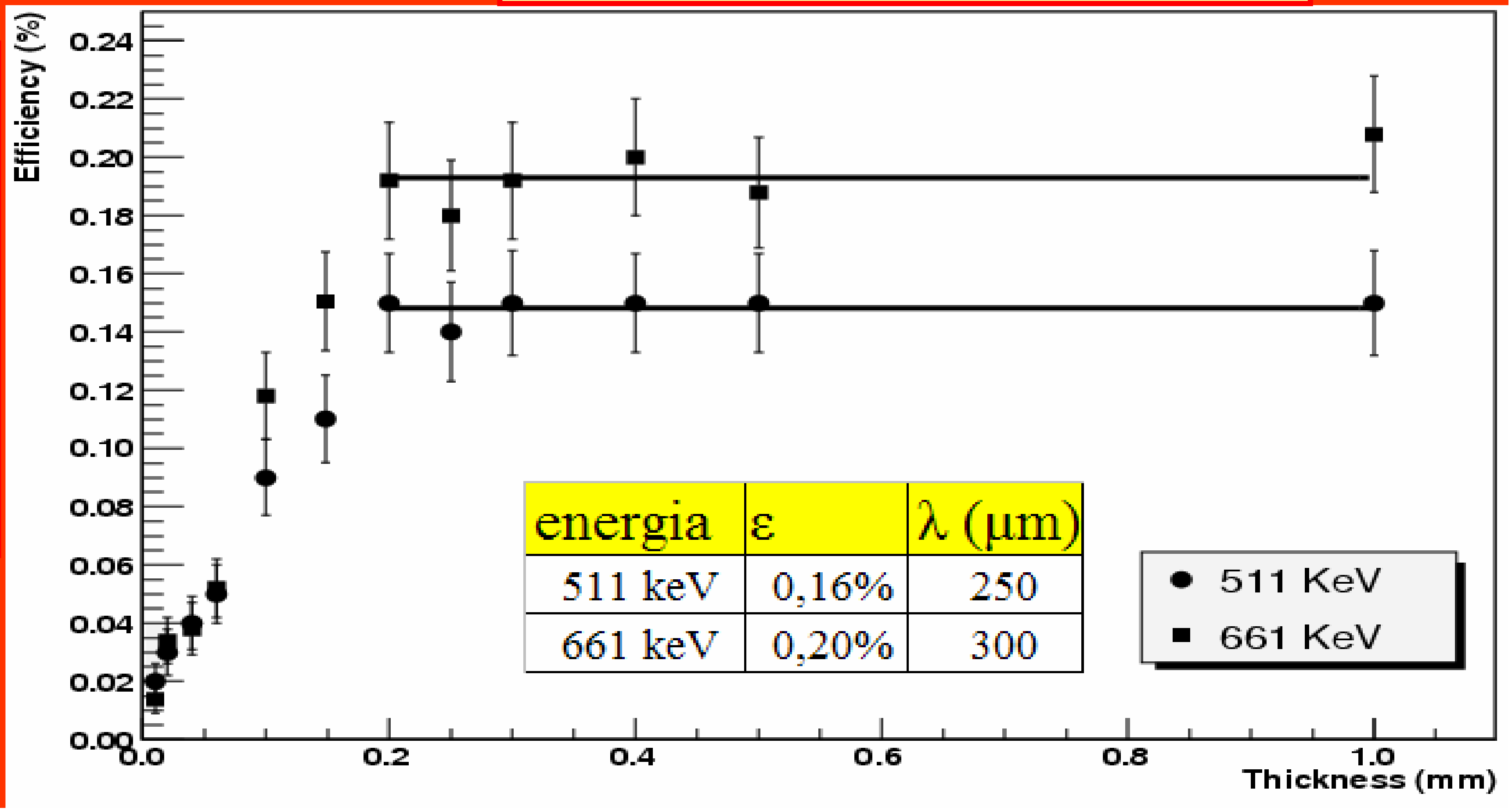


Monte Carlo simulation of $\varepsilon_{\mathrm{conv}}$

$$\varepsilon_{conv} = \frac{\text{exiting electrons}}{\text{incident photons}} \quad vs. \;\; \text{thickness}$$

Linear growth: the glass thickness is smaller than the average range of emitted electrons.

No needs to make thicker glasses since only the last layers of the electrodes (faced to the gap) contribute to the signal

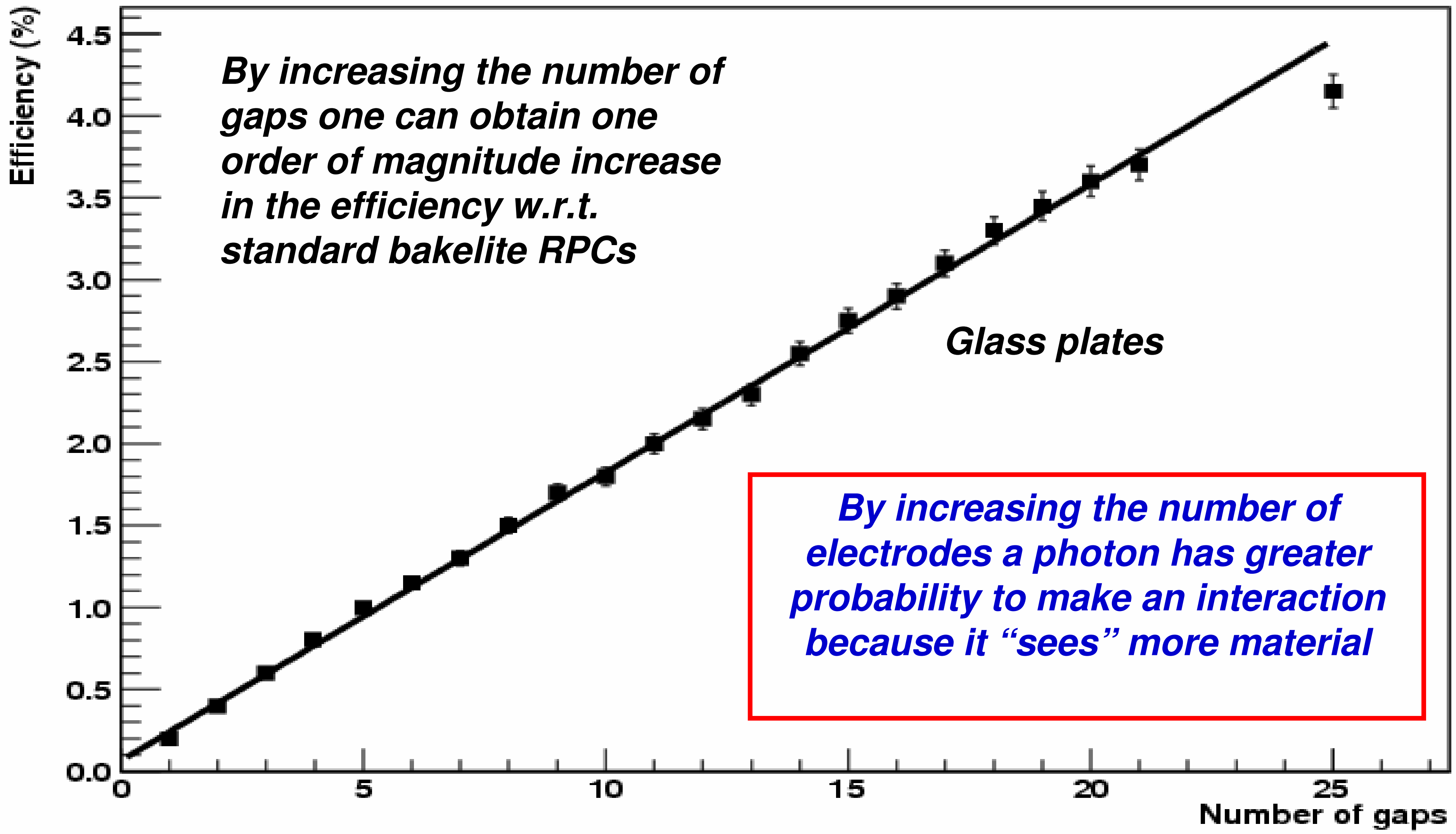


energia	ε	λ (μm)
511 keV	0,16%	250
661 keV	0,20%	300

L. Litov

Number of gaps

(Monte Carlo simulation – GEANT4)



By increasing the number of gaps one can obtain one order of magnitude increase in the efficiency w.r.t. standard bakelite RPCs

By increasing the number of electrodes a photon has greater probability to make an interaction because it "sees" more material

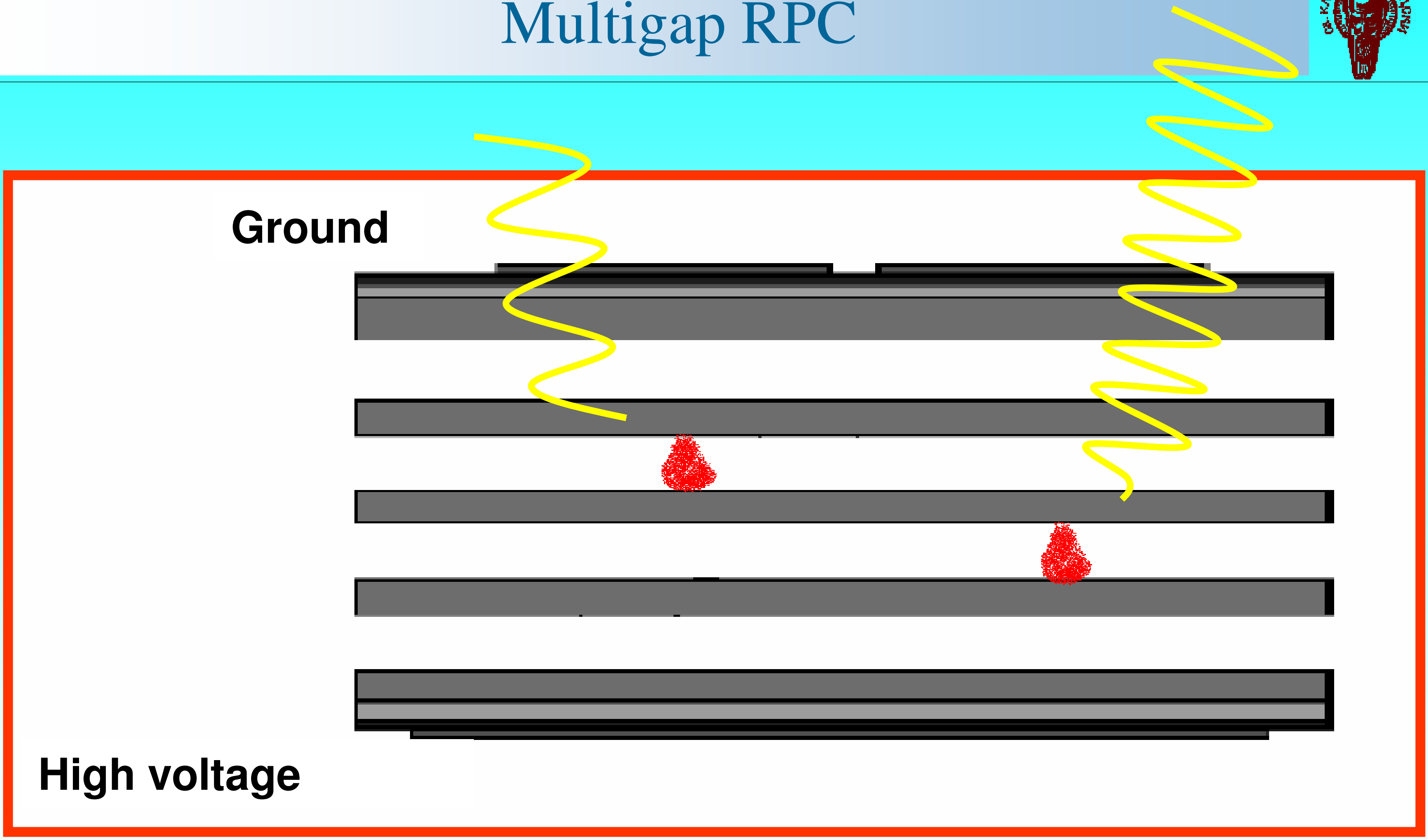
Recipe

- *Adequate thickness electrodes*
- *Increase the number of gaps*
- *Reduce also the gas thickness*

(the probability of interaction of a photon in the gas is low)

- *→ Better time resolution*

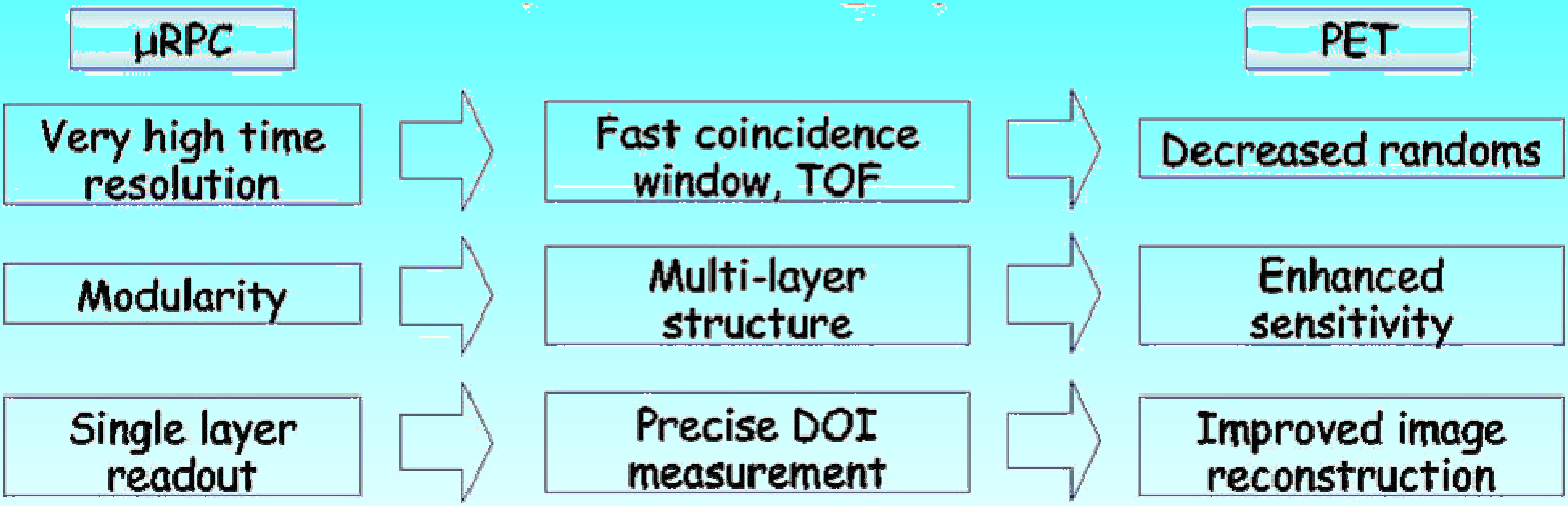
Multigap RPC



Gas gaps (300 µm)

$(85\% \; C_2H_2F_4, \; 5\% \; i\text{-}C_4H_{10}, \; 10\% \; SF_6)$

RPC



μRPC

PET

Very high time resolution → Fast coincidence window, TOF → Decreased randoms

Modularity → Multi-layer structure → Enhanced sensitivity

Single layer readout → Precise DOI measurement → Improved image reconstruction

RPC vs Scintillator

Scintillator

- Expensive crystals
- Requirements:
- High efficiency
- Good time resolution
- Good energy resolution
- 25-30 mm long crystals
- 4x4 mm^2 face
- The space resolution is limited by the parallax

RPC

- Cheaper
- Able to work in strong magnetic fields
- There is no parallax
- Easy to cover big surface
- (large FOV)
- Fast detectors
- Good time resolution (50 ps)
- Good space resolution (500 µm)

Comparison with crystals

Parameters:

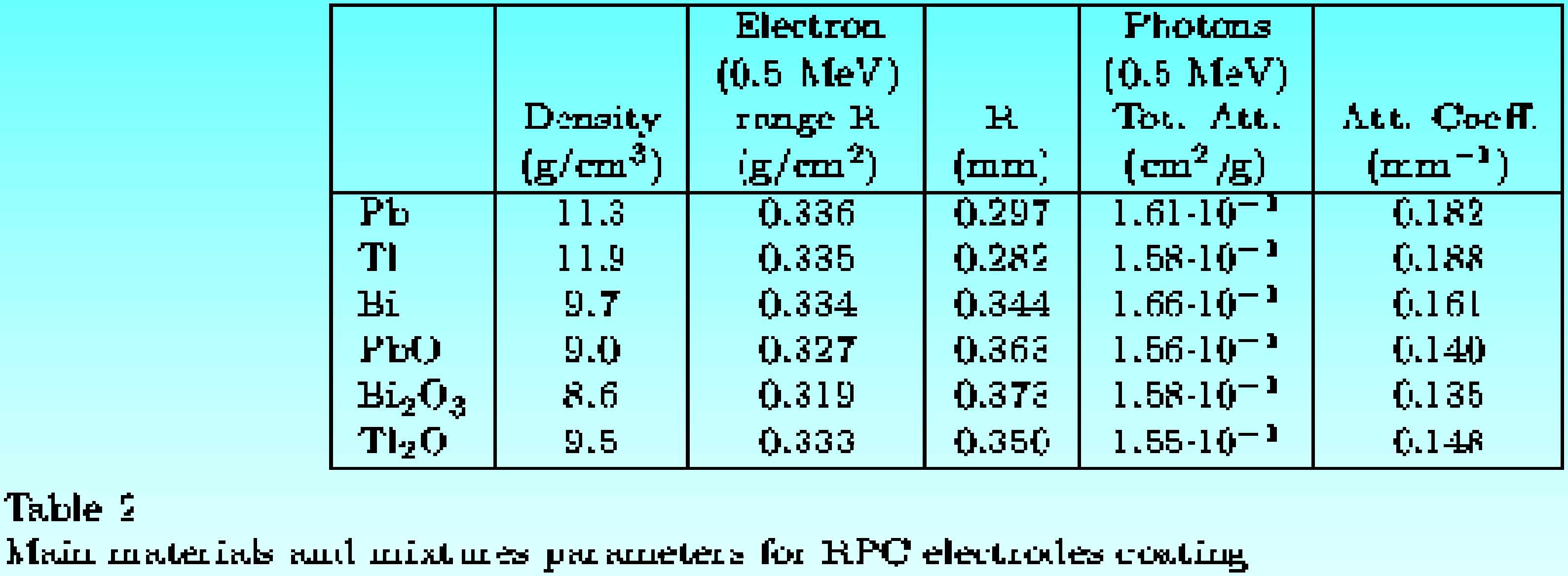
1) **Efficiency**

2) **Time resolution**

3) **Energy resolution**

4) **Cost**

Efficiency - Possible coating materials



	Density (g/cm^3)	Electron (0.5 MeV) range R (g/cm^2)	R (mm)	Photons (0.5 MeV) Tot. Att. (cm^2/g)	Att. Coeff. (mm^{-1})
Pb	11.3	0.336	0.297	$1.61 \cdot 10^{-1}$	0.182
Tl	11.9	0.335	0.282	$1.58 \cdot 10^{-1}$	0.188
Bi	9.7	0.334	0.344	$1.66 \cdot 10^{-1}$	0.161
PbO	9.0	0.327	0.363	$1.56 \cdot 10^{-1}$	0.140
Bi_2O_3	8.6	0.319	0.373	$1.58 \cdot 10^{-1}$	0.135
Tl_2O	9.5	0.333	0.350	$1.55 \cdot 10^{-1}$	0.148

Table 2
Main materials and mixtures parameters for RPC electrodes coating

Other possibility is to use metal (heavy) electrode RPC

Time resolution

Typical time resolution of BGOs is 3 ns ?

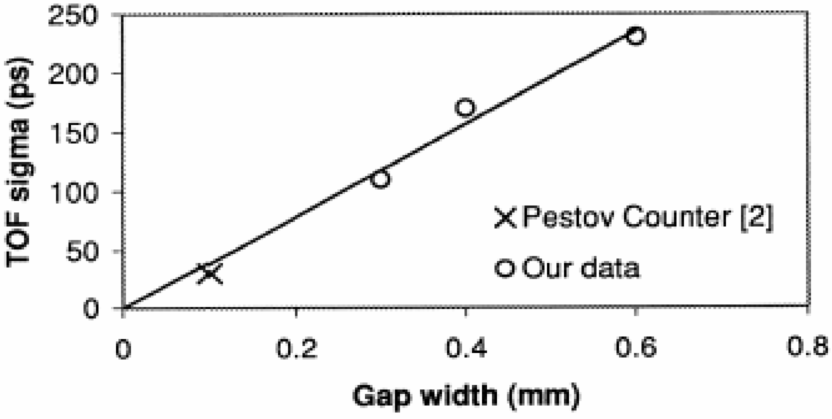
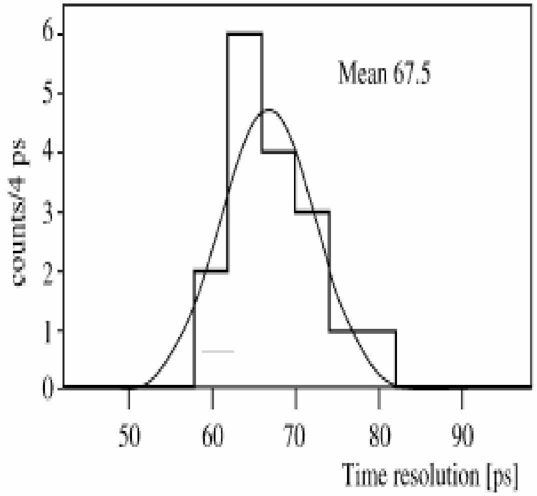


Fig. 6. Tests performed with other detectors featuring different widths of the gas gap suggest that the main contribution to the time jitter is associated to the amplification process in the gas. The timing resolution seems to depend almost linearly on the gap width, with a slope of approximately 40 ps/0.1 mm.

→P.Fonte

52 ps with 1 gap

Fonte & Williams

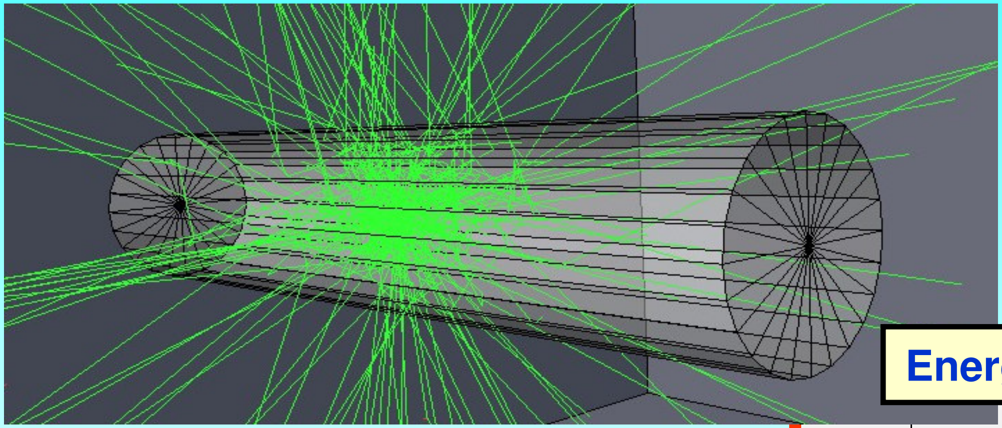


Alice

Better time resolution
means

Less random coincidences and measurement of TOF

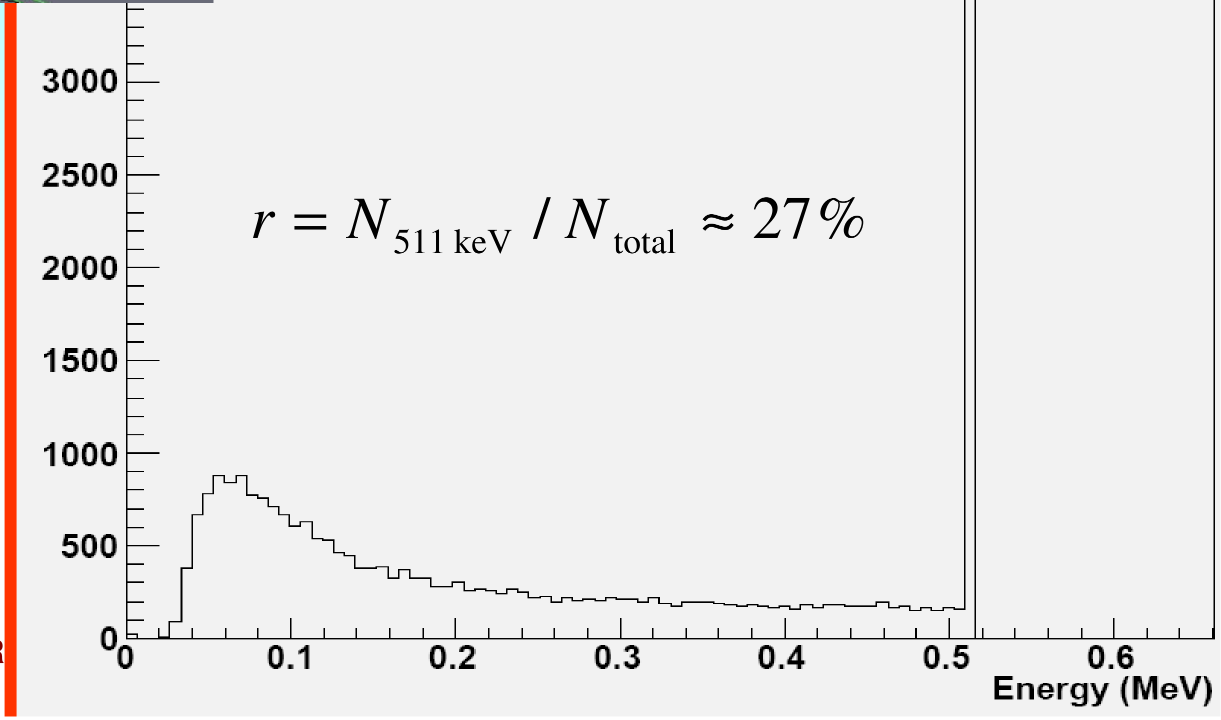
Energy resolution (response function)



Geometry for the simulation study on the gamma energy spectrum from annihilation

Real Scatter fraction 3D PET up to 60%

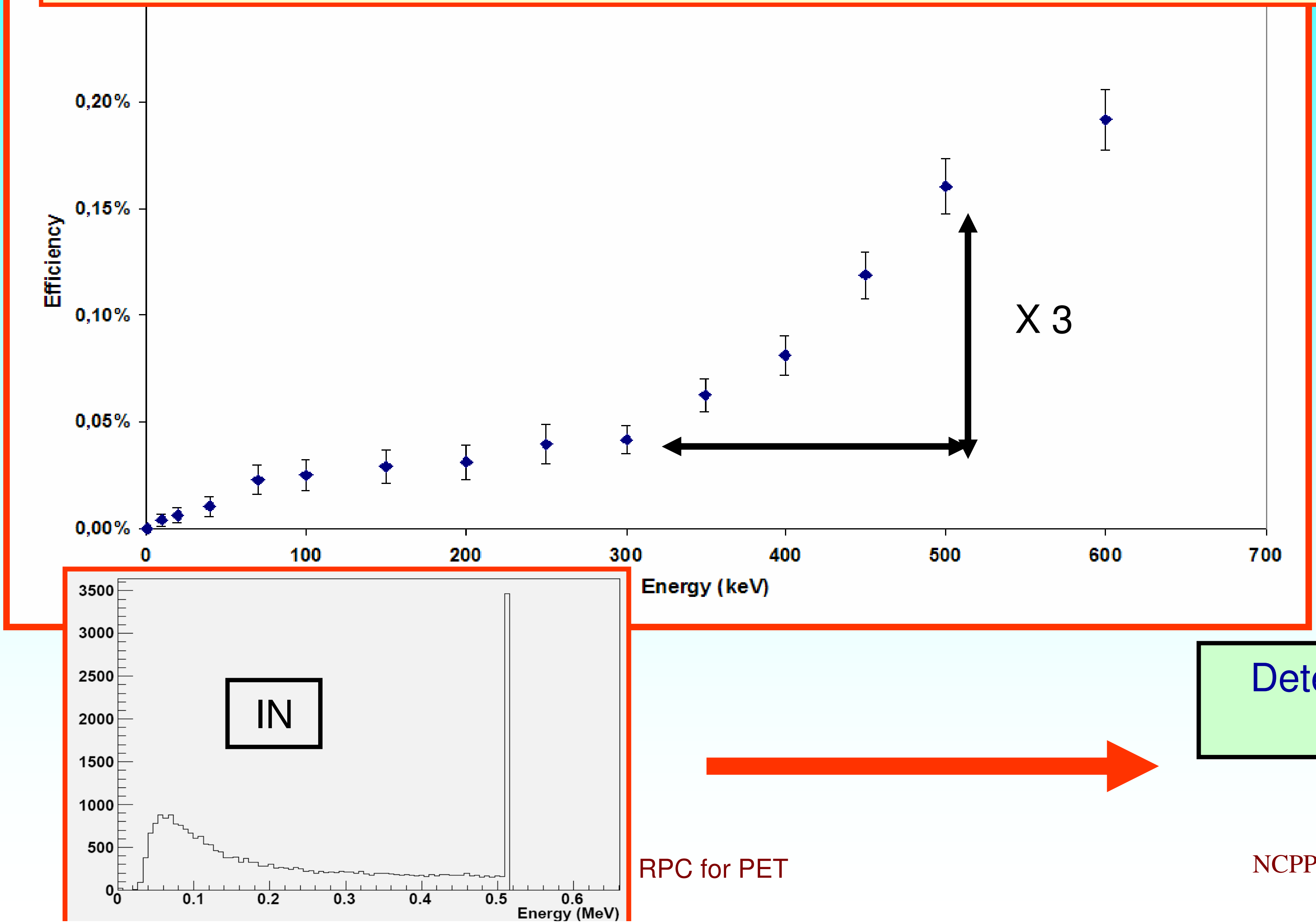
Energy spectrum of exiting photons



$$r = N_{511\ \mathrm{keV}} \,/\, N_{\mathrm{total}} \approx 27\%$$

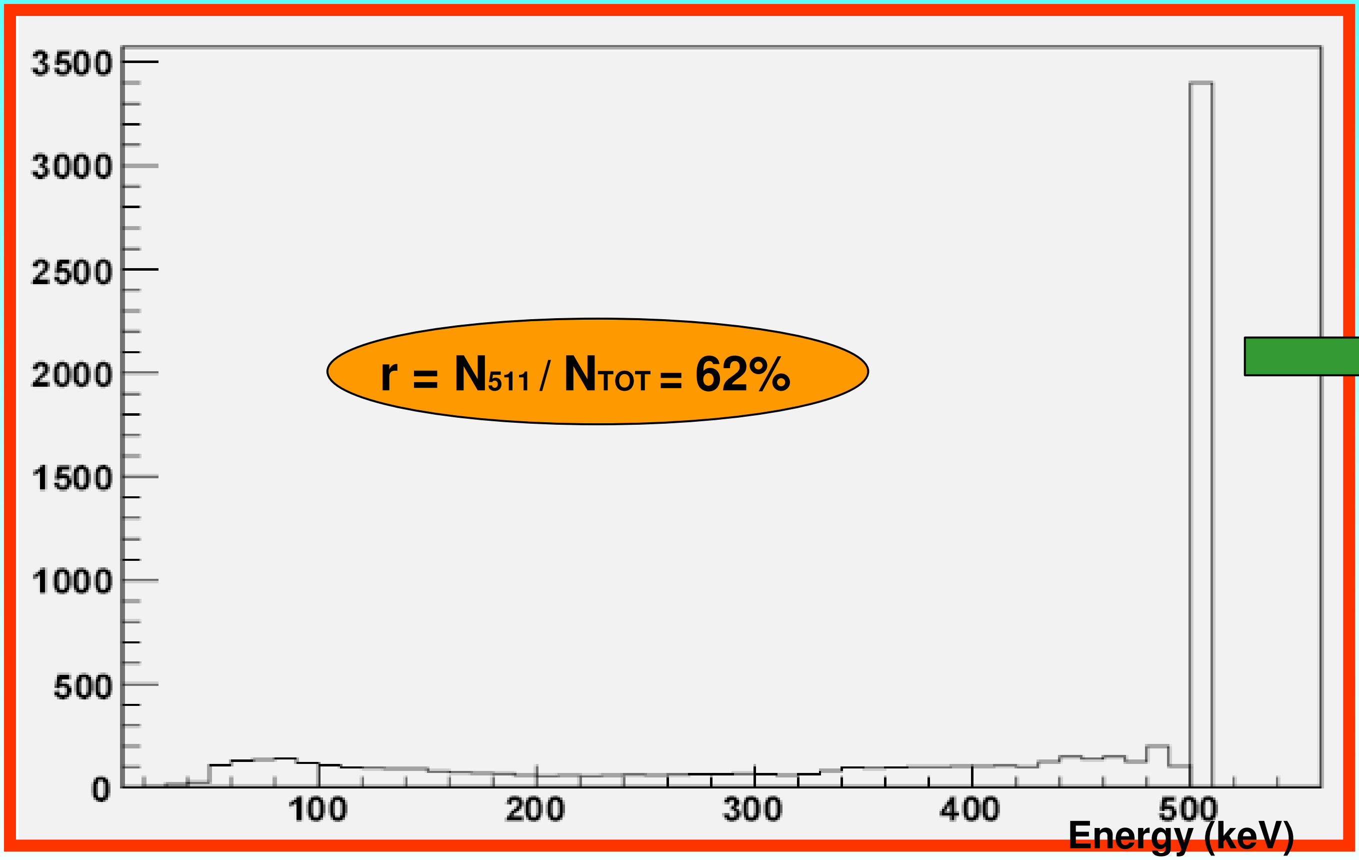
Energy resolution (response function)

MRPC efficiency (1 gap) vs incident gamma energy



Detected gamma spectrum

Energy resolution (response function)



$r = N_{511} / N_{TOT} = 62\%$

Reduction of coincidences

from scattering

Cost: The average cost per unit surface would be at least 10 time less vs. crystals

RPC for PET

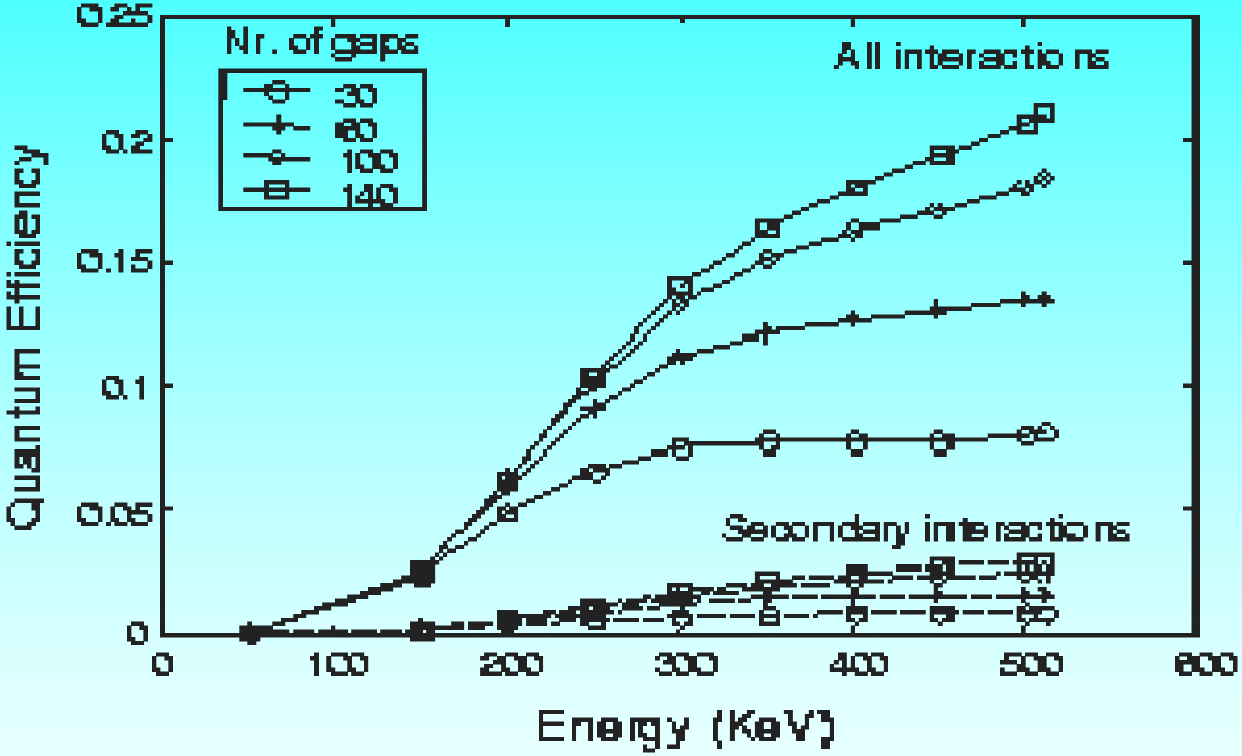


Fig. 2. Simulated (GEANT4) quantum efficiency as a function of the incident photon energy for a stack of counters (see Fig. 1). For a large number of plates the values scale almost linearly with the energy above ~ 100 keV. Only a small fraction of the secondary interactions (from counter-scattered photons) is visible.

Possible directions

- Human PET
  - Requires
  - High spatial resolution ~ 1 mm
  - Very good time resolution (TOF)
  - Cover big surface (full body PET)
  - Fast data collection (to look at dynamics of the processes)
  - Good simulation and correction for the scattering inside the body

- Small animals PET
  - Better spatial resolution (<1 mm)
  - Good timing for suppression of the random coincidence

- Difference
  - In human PET – measure time of flight of the two gammas
  - In small animals – narrow coincidence gate - suppression of random coincidences

Possible directions

RPC construction

- Goals:
  - ✓ Efficiency ~ 20%
  - ✓ Spatial resolution – better 500 μm
  - ✓ Time resolution - < 50 ps
- Construction
  - ✓ The electrodes are made from glass (200 – 300 μm),
  - ✓ one with special coating (<200 μm)
  - ✓ Gas gap – 200 or 300 μm

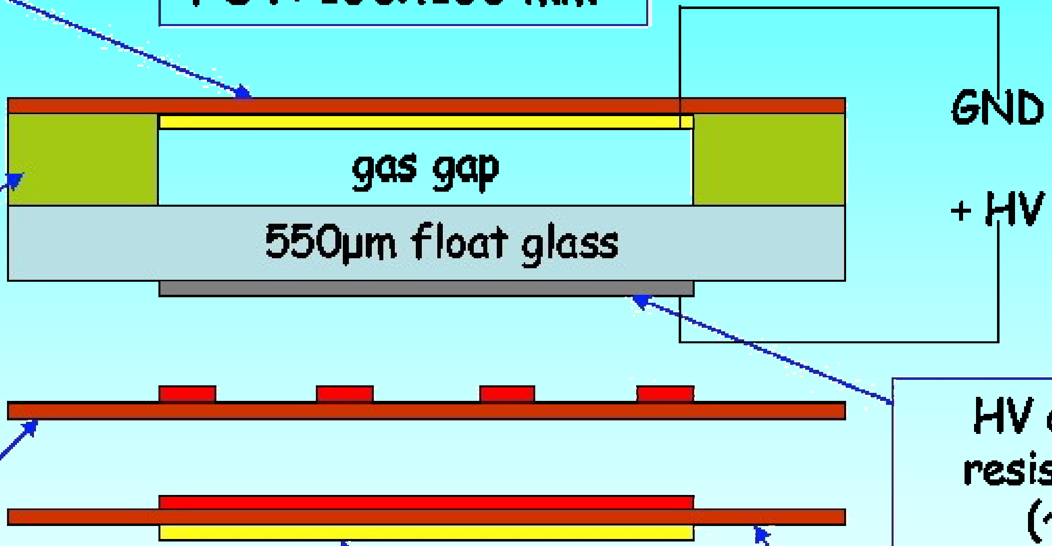
  - ✓ One electrode is glass,
  - ✓ second metal (Bi, Cu, Pb, Au) - thickness 3 – 20 μm

- Multigap

Hybrid RPC

Hybrid: the anode is resistive (glass), the cathode is conductive (gold)

FOV: 100x100 mm^2



50µm kapton with 3µm gold film

500µm FR4 spacers outside active area

HV distribution resistive coating (~1MΩ/□)

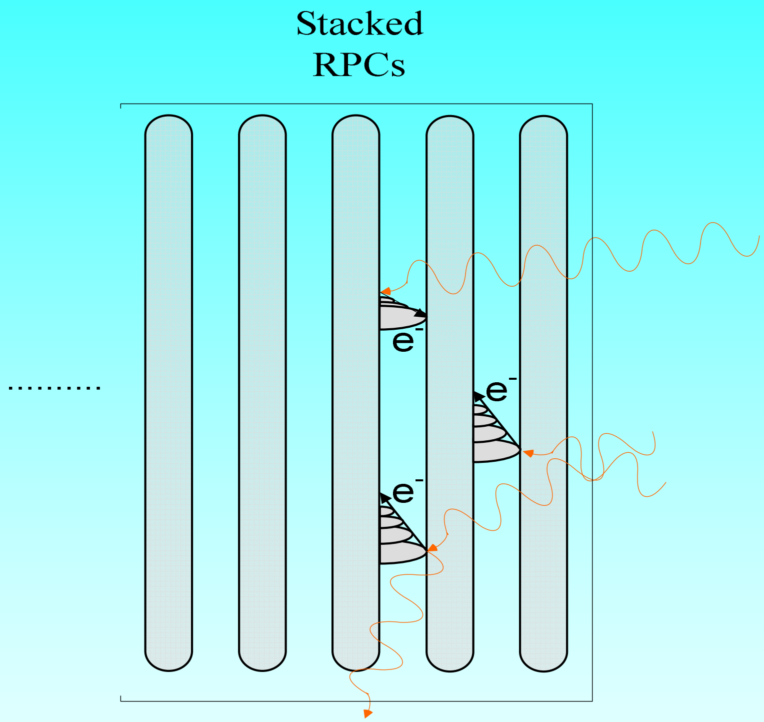
50µm kapton with 5µm X-strips

kapton circuit supports the cathode of the following layer

50µm kapton with 5µm Y-strips

Many single layers are stacked to realize one detector

Small animal PET with RPCs



Use the plates as a γ convertor

- **High geometry acceptance** > 90%.
- Fully 3D measurement of the interaction point of the photon => **No parallax error**.

- **Sub-millimetre spatial resolution.**
- **High timing resolution ~ 0.3 ns FWHM***
- Moderate Efficiency.

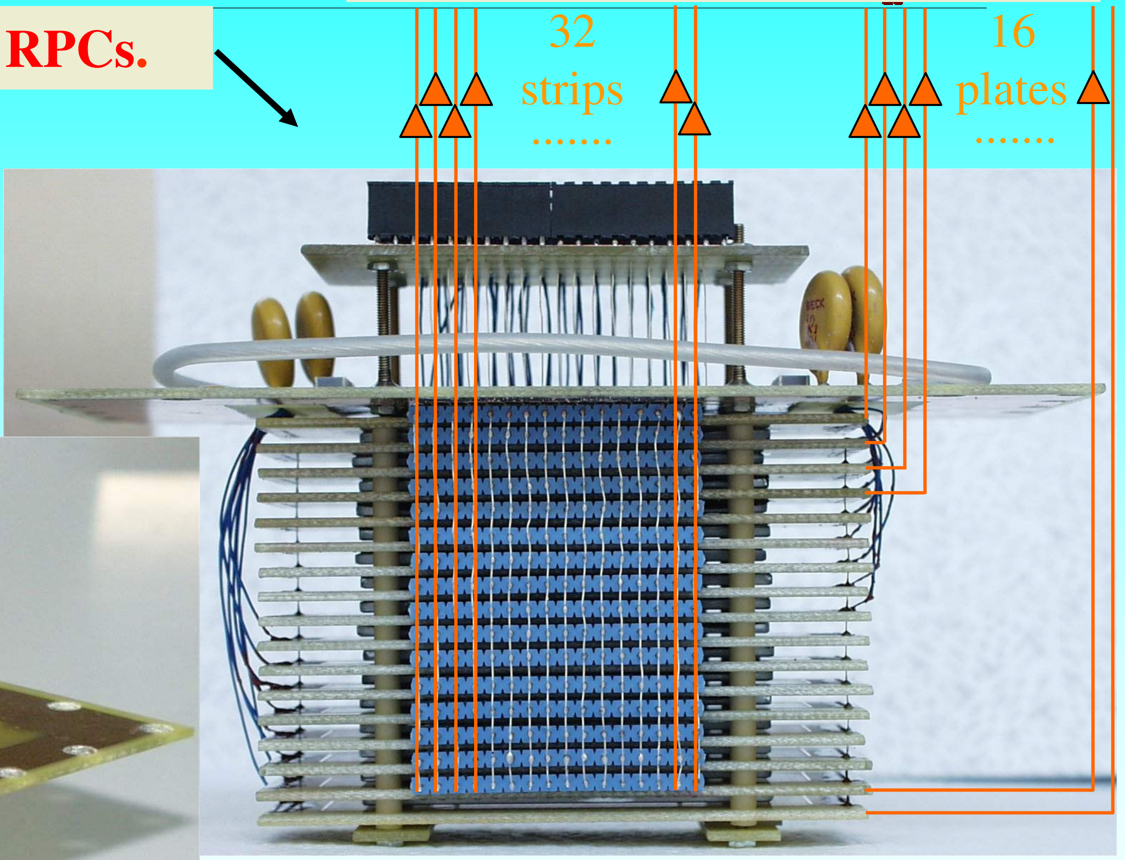
- Compatible with Magnetic Resonance Imaging.

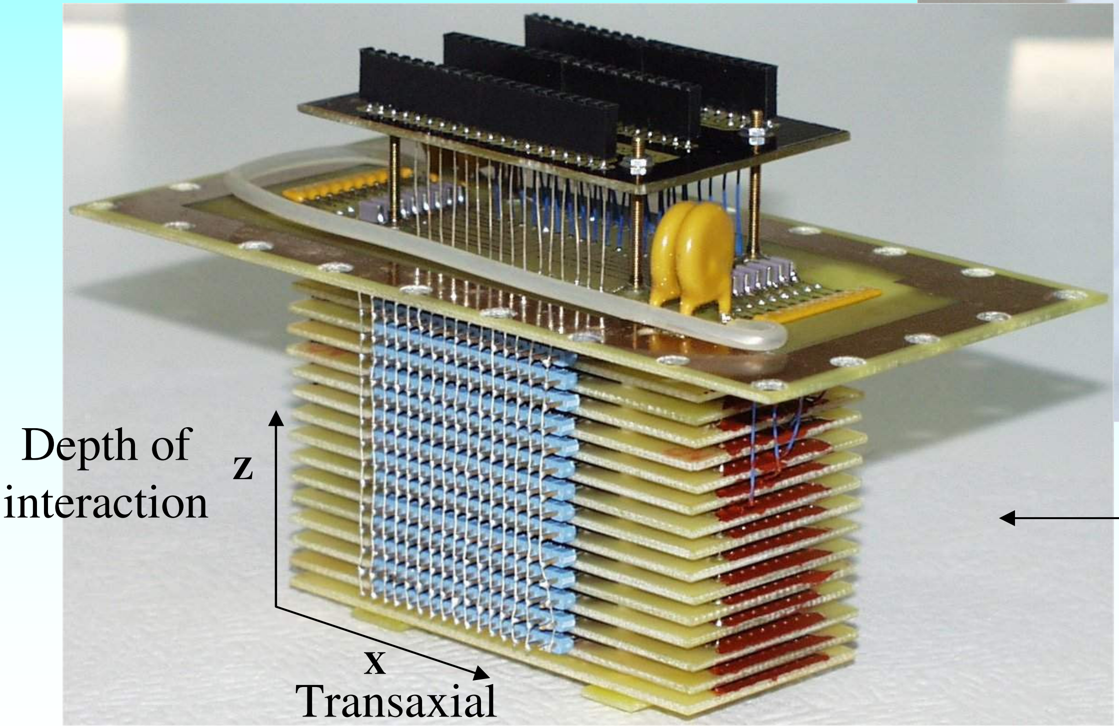
* *Nucl. Instr. And Meth A, 443 (2003) 88-93*

Charge-sensitive electronics allowing interstrip position interpolation

16 stacked RPCs.

Aimed at **verifying** the concept and show the **viability** of a **sub-millimetre spatial resolution**.



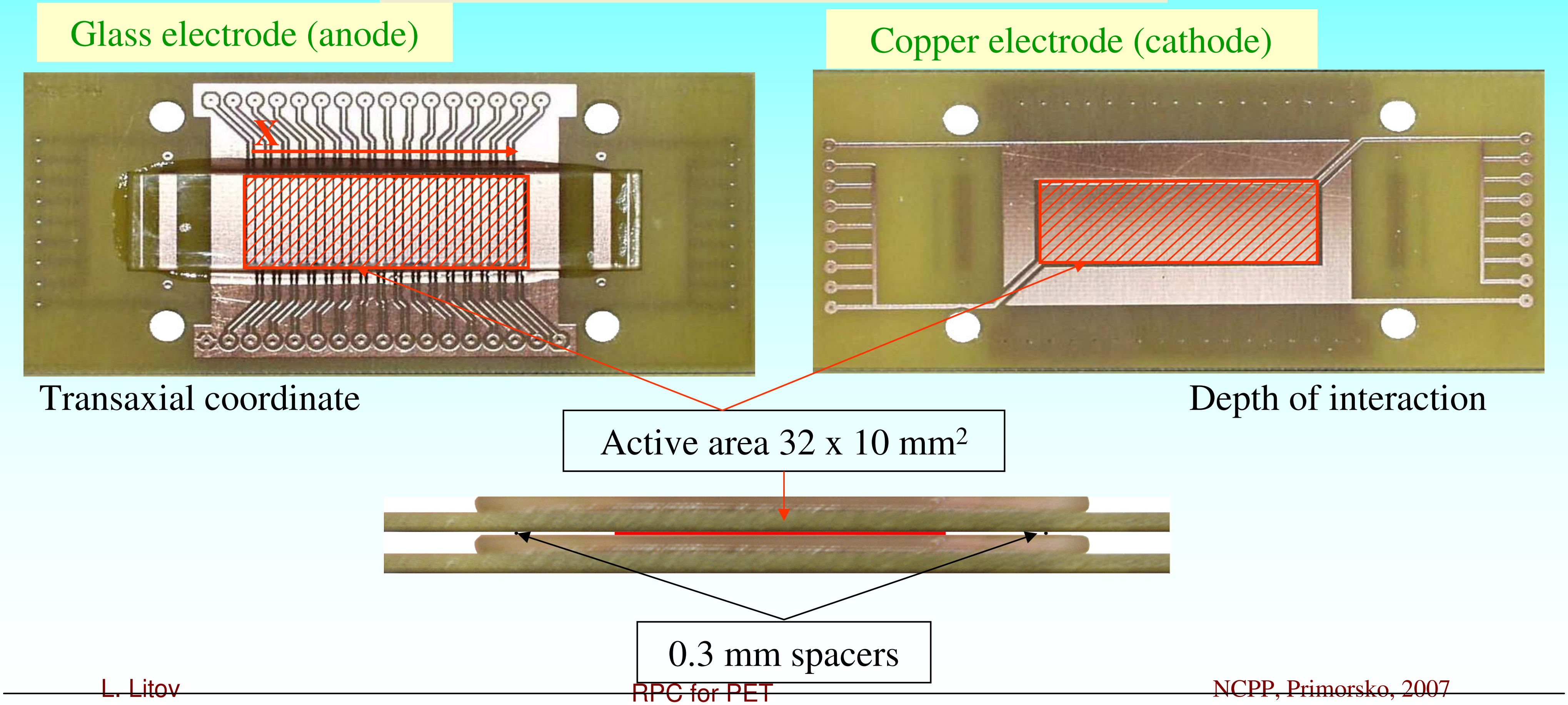


2D measurement of the photon interaction point.

3D measurement possible *NIMA 508 (2003) 70–74*

Small animal PET

- **Copper** (on a PCB) and **glass electrodes**.
- 32 1-mm wide X pickup strips.
- 0.3 mm Gap.
- Not optimized for high efficiency.



Glass electrode (anode)

Copper electrode (cathode)

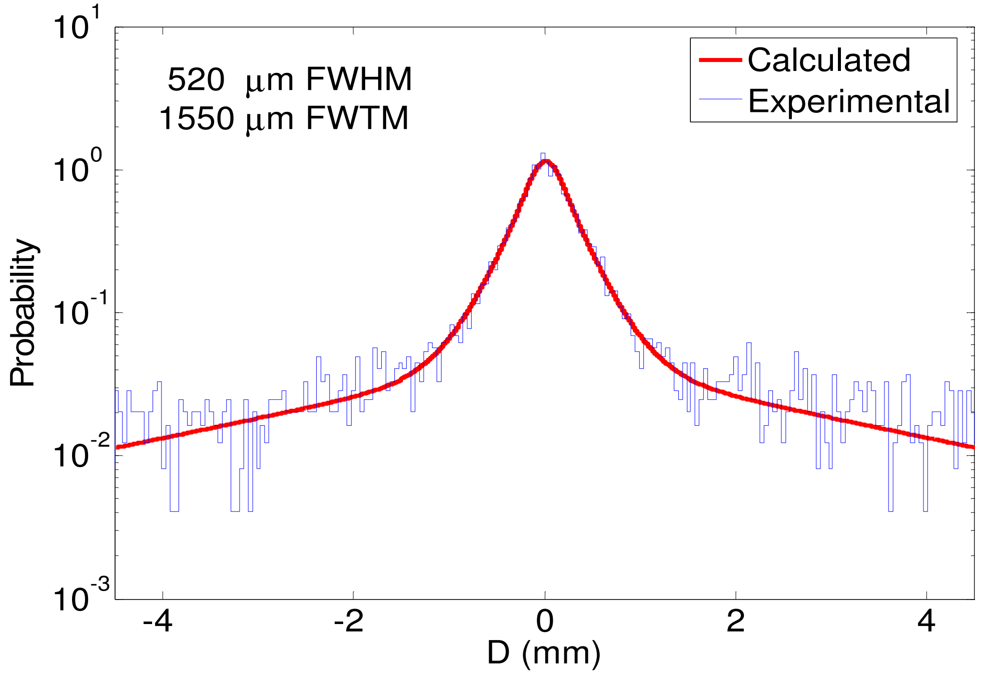
Transaxial coordinate

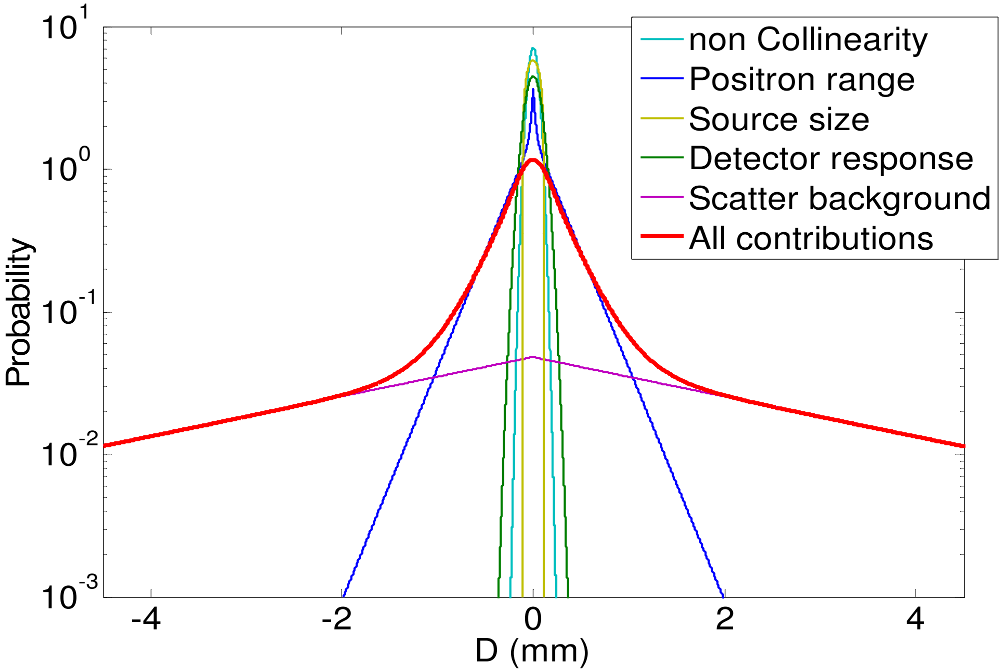
Depth of interaction

Active area 32 x 10 mm^2

0.3 mm spacers

Intrinsic spatial resolution





- Annihilation photon n

Phys. Med. Biol. 44 (1999) 781-799.

$N(x) = exp(-x^2/2\sigma^2)$, where FWHM = 2.35σ = 0.0022a_s with a_s the system diameter (mm).

- **Positron range.**

$K_2 = 3.75\ mm^{-1}$

- **Source size.**

$S(x)=sqrt(size^2 - x^2)$, where *size* is the source radio (mm).

- **Detector response.**

$FWHM_{det} = 220\ \mu m$

- **Scatter background.**

$C_2 = 0.04$, $K_3 = 0.32\ mm^{-1}$

$R(x) = C2(N(X)\otimes P(X)\otimes D(X)\otimes S(X))+(1-C2)SC(X)$

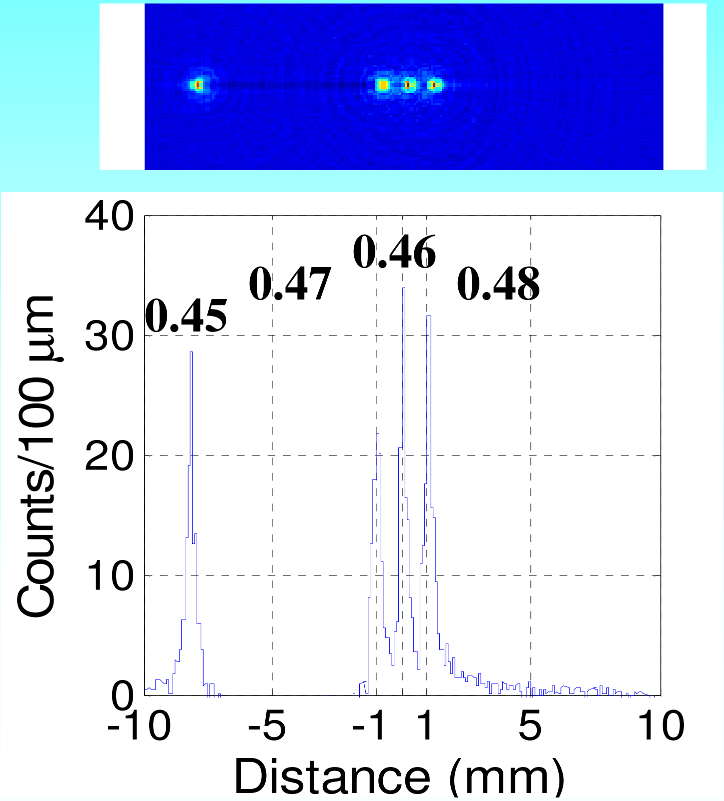
520 µm FWHM

1550 µm FWTM

Image spatial resolution.

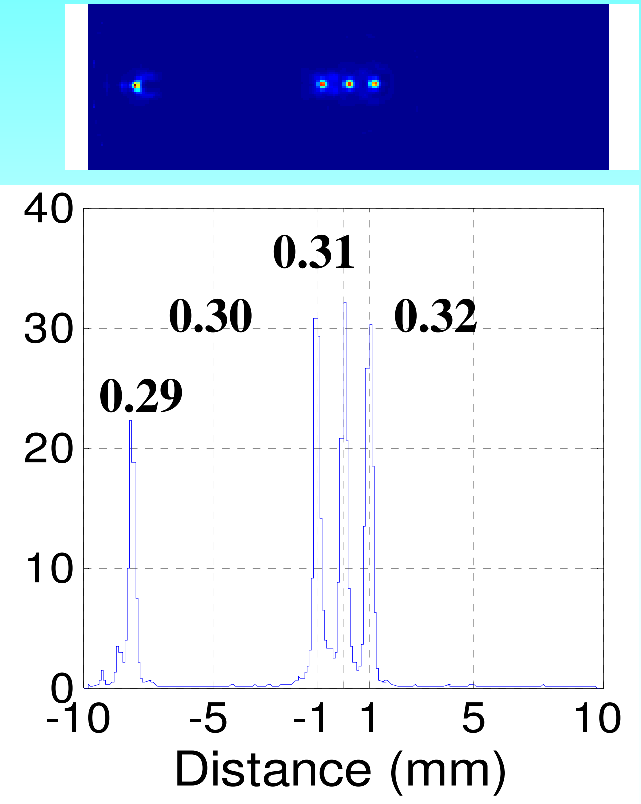
Filtered Back Projection FBP

~ 465 µm FWHM



Maximum likelihood-expectation maximization with resolution modeling (ML-EM)

~ 305 µm FWHM



Homogeneous spatial resolution over the entire detector

Comparison between different small animal PET parameters and the expected parameters of the RPC-PET.

Scanner	**Image spatial Resolution, FBP (mm)**	Time resolution (ns FWHM)	FOV (mm Ø x mm)	Central point absolute sensitivity (cps/kBq)	Source (mm Ø x mm)	**Peak NEC (Kcps)**
microPET II® [1],[2]	**1.1**	3	160 x 49	23 - 33	25 x 70 mouse size	**235** at ~2.35 MBq/cm^3
microPET Focus F120 [6]	**1.75**	6	147 x 76	71	mouse size	**809** at ~88 MBq
YAP-PET [3],[4]	**1.6**	2	40 x 40	18 at (Ø = 150 mm)	-	**90** (not peak) at ~16.6 MBq
Quad HIDAC (32 modules) [5]	**0.95**	-	170 x 280	18	-	**100** at ~0.2MBq/cm^3
RPC-PET	**0.47**	0.3	60 x 100	21	25 x 70 mouse size	**318** at ~ 2.63 MBq/cm^3

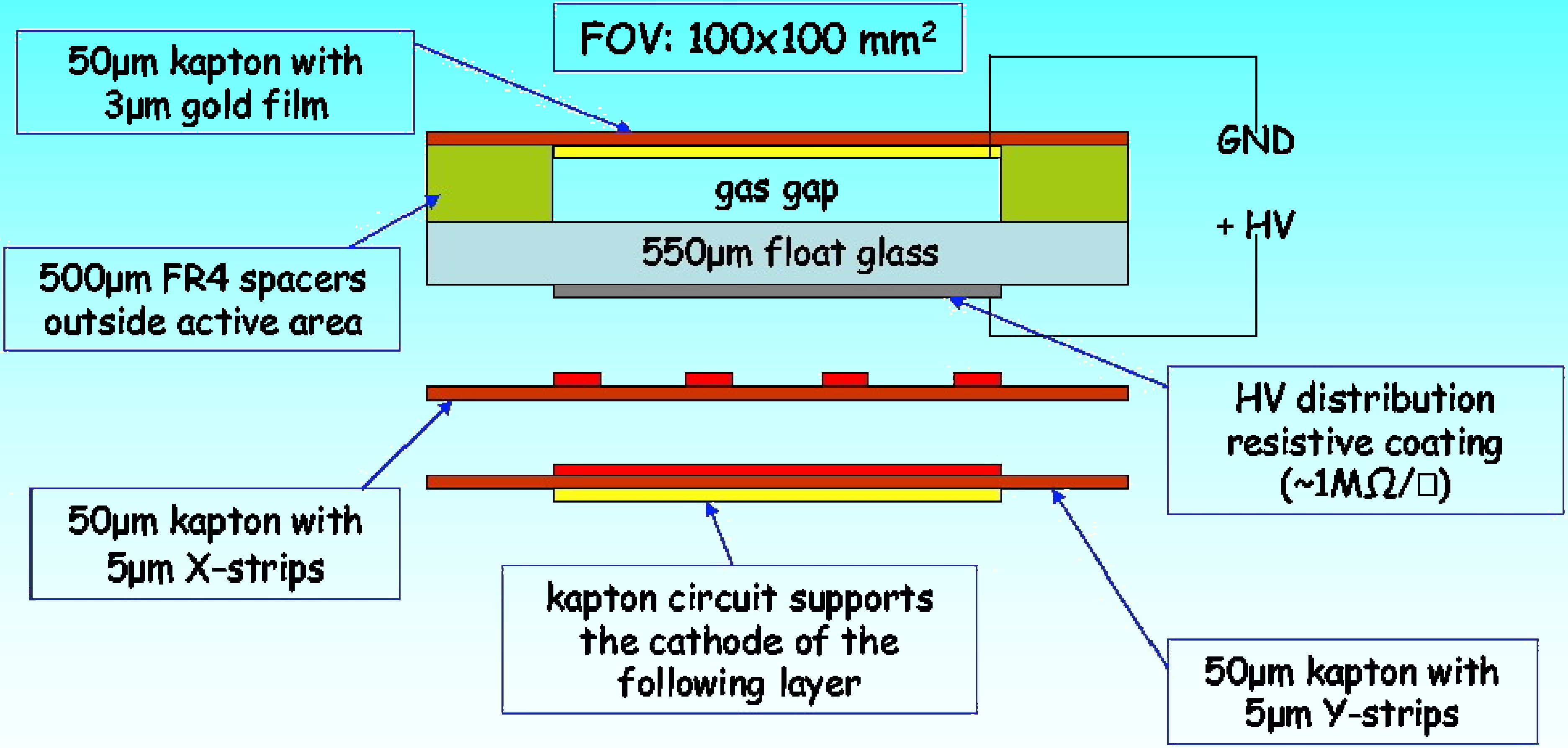
1. Yuan-Chuan Tai et al., "MicroPET II: design, development and initial performance of an improved MicroPET scanner for small-animal imaging", *Phys. Med. Biol.* 48 (2003) 1519-1537.
2. Yongfeng Yang, et al., "Optimization and performance evaluation of the microPET II scanner for in vivo small-animal imaging", Phys. Med. Biol. 49 (2004) 2527-2545.
3. A. del Guerra, G. Di Domenico, M. Scandola, G. Zavattini, "YAP-PET: first results of a small animal Positron Emission Tomograph based on YAP:Ce finger crystals", IEEE Trans. Nucl. Sci., vol 45, No. 6 December 1998, 3105-3108.
4. G. Di Domenico et al., "Characterization of the Ferrera animal PET scanner", Nucl. Instr. And Meth. A, 477 (2002) 505-508.
5. A.P. Jeavons, R.A. Chandler, C.A.R. Dettmar, "A 3D HIDAC-PET Camera with Sub-millimetre Resolution for Imaging Small Animals", IEEE Trans. Nucl. Sci., vol. 46, No. 3, June 1999, 468-473.
6. Richard Laforest et al. "Performance Evaluation of the microPET – Focus F120", presented at IEEE NSS/MIC Rome 2005.

University of Pavia

Fig. 5. a- glass MRPC prototype being assembled; b- 2 mm readout strips facing the detector; c- visualization of simulated tracks in aluminum case.

Hybrid RPC

Hybrid: the anode is resistive (glass), the cathode is conductive (gold)



FOV: 100x100 mm^2

50µm kapton with 3µm gold film

500µm FR4 spacers outside active area

HV distribution resistive coating (~1MΩ/□)

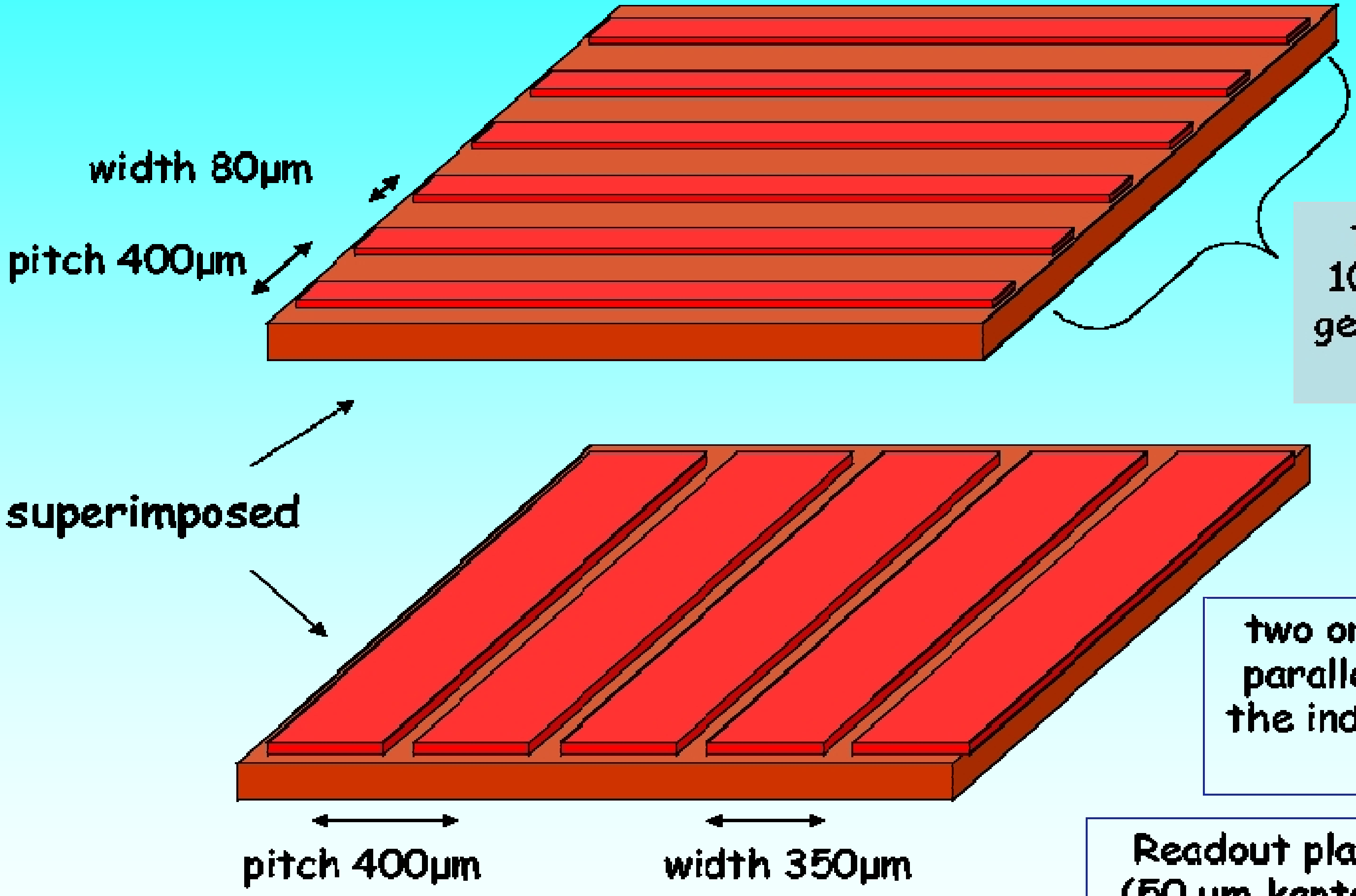
50µm kapton with 5µm X-strips

kapton circuit supports the cathode of the following layer

50µm kapton with 5µm Y-strips

Many single layers are stacked to realize one detector

Readout Details



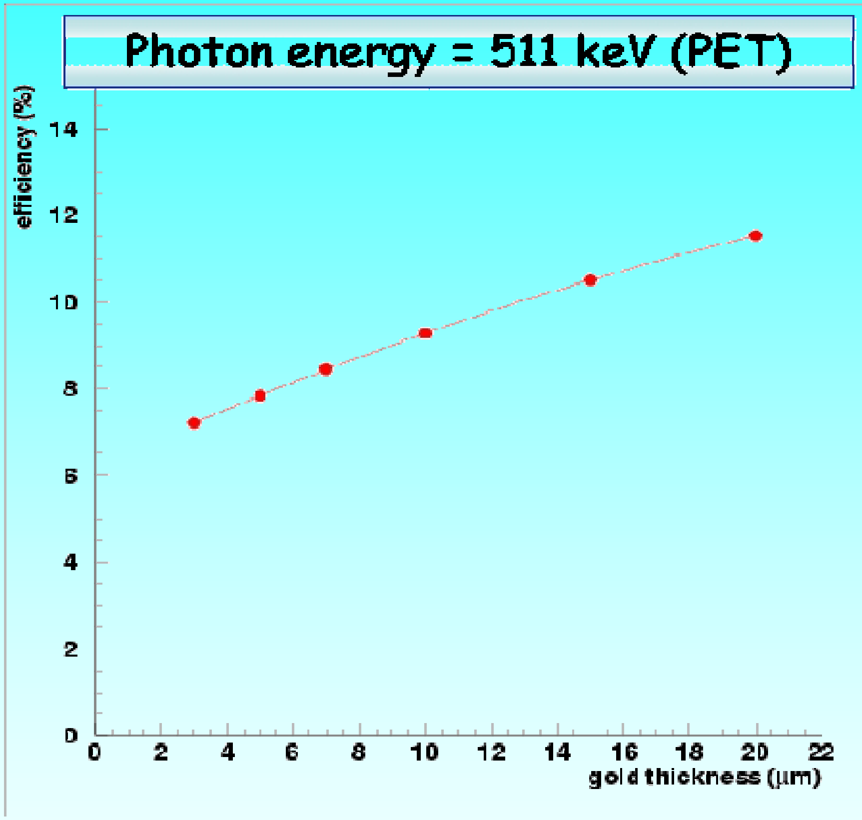
the strips are 10-fold ORed to get 4 mm readout pitch

two orthogonal sets of parallel strips perform the inductive readout of the signal

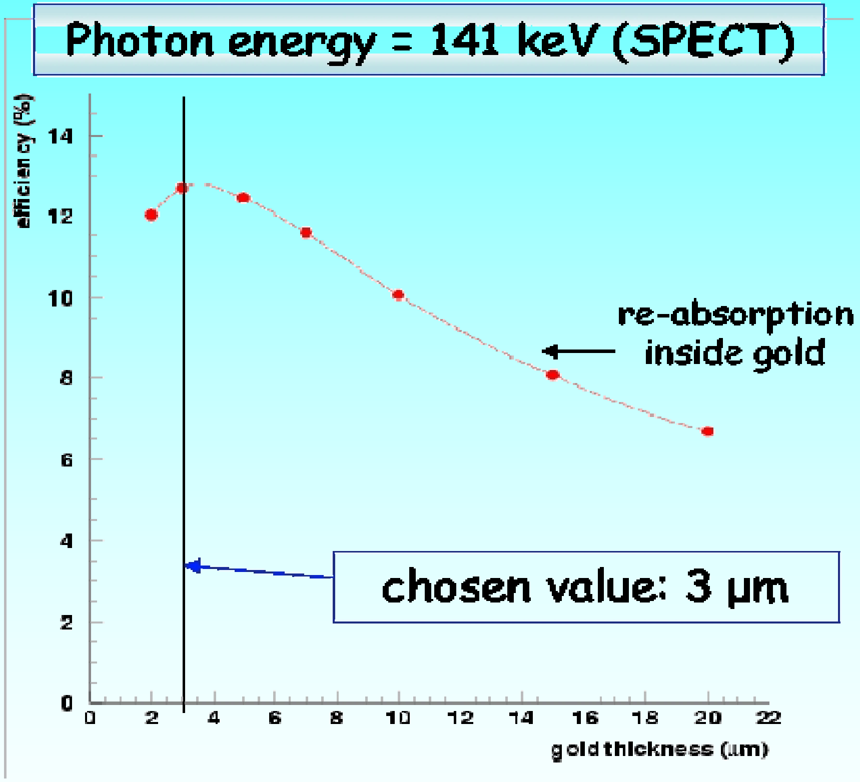
Readout planes made of PCB (50 µm kapton + 5 µm copper)

Efficiency vs gold thickness

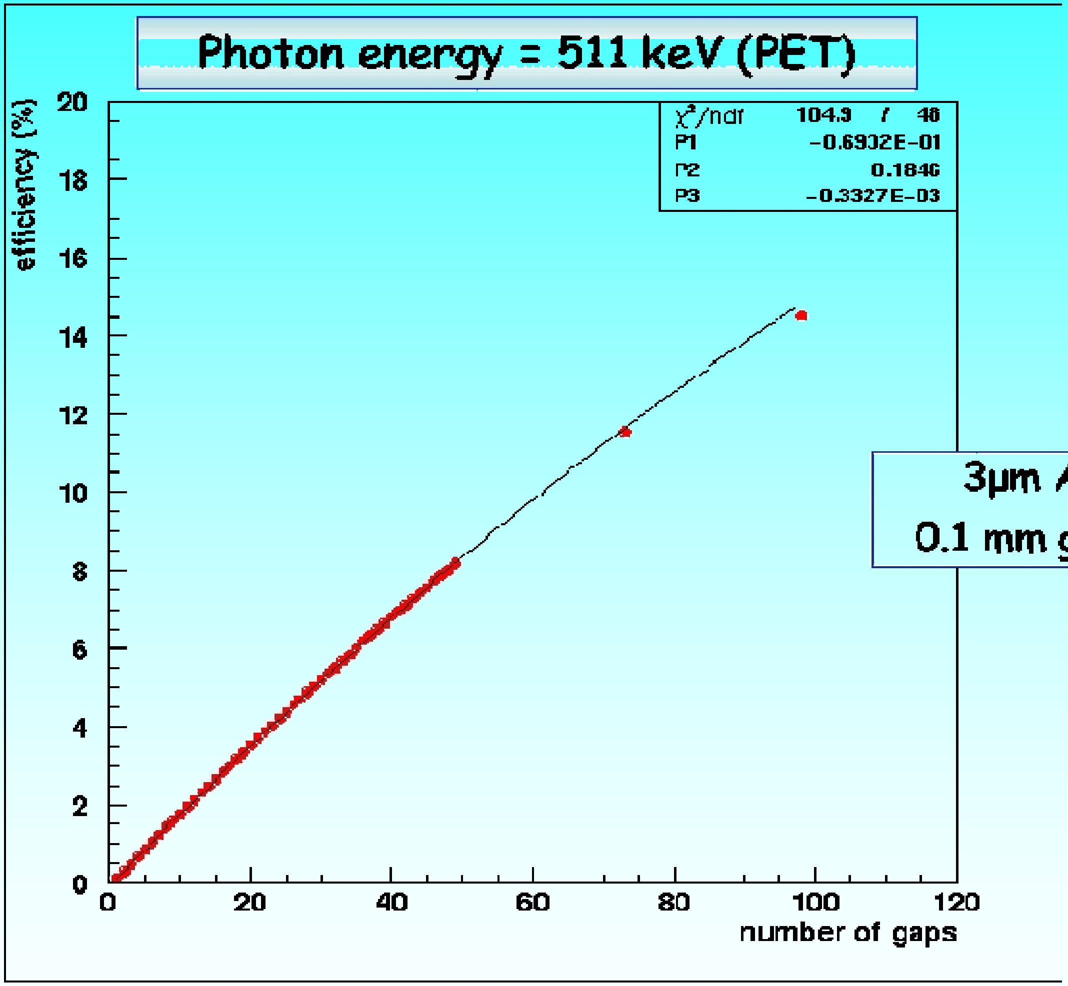
All simulations performed with FLUKA



48 gaps



Efficiency vs number of gaps



Photon energy = 511 keV (PET)

3μm Au

0.1 mm glass

RPCPET Project

- **Understanding of the processes inside the body**
  - Phantoms – commercial or specially designed and build
  - MC simulation (GEANT4, GATE)
  - Measurement of the phantoms and comparison with simulations
- ✓ Goal –
  - ✓ corrections for the reconstruction (scattering, absorption etc)
- **Detector design and construction**
  - In parallel – several options (glass -glass, glass - metal, different readouts)
  - Simulation of the detector response (GEANT + GARFIELD)
  - Production of prototypes
  - Measurements with point like sources and phantoms
  - Tests in strong magnetic and high frequency electric fields (MRI)
- ✓ Goal –
  - ✓ choose more suitable construction (can be different for human and animal PET)
  - ✓ Proof RPC ability to work with MRI

RPCPET project

- **Electronics**
  - Analog – charge sensitive preamplifiers
  - Measurement of the amplitude (if required) – ADC - (possible dependence of time from amplitude)
  - Measurement of the time – TDC (possible dependence of time from amplitude)
  - Trigger electronics (possibly using cathode information)
  - Data storage
- **Slow control system**
  - HV
  - LV
  - Gas system
  - Temperature and pressure control
- **Image reconstruction**
  - New detector requires specially designed reconstruction taking into account specific detector properties (different backgrounds, corrections, calibration, alignment etc)
  - Combine reconstruction with MC simulations for every particular patient

RPCPET project

- ❑ Goal of the project
- ➢ Build full prototype – one ring
- ➢ Fully functioning system
- ➢ Test together with MRI

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  - INRNE of BAS
  - IPP of BAS
  - Tokuda hospital
  - LTD in Physics

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